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MULTISPECTRAL RESOURCE SAMPLER WORKSHOP

SUMMARY REPORT
OF WORKSHOP HELD
MAY 31-JUNE 1, 1979
AT
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

JUNE 1979

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND 20771

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Silver Spring, Maryland 20910

MULTISPECTRAL RESOURCE SAMPLER

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ORI, INC.
1400 SPRING STREET
SILVER SPRING, MARYLAND 20910

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ACRONYMS AND ABBREVIATIONS USED IN THIS REPORT

C.C.T.	Computer Compatible Tapes
C.S.U.	Colorado State University
EIFOV	Estimated Instantaneous Field of View
ERIM	Environmental Research Institute of Michigan
FOV	Field of view
FPA	Focal plane assembly
GSFC	Goddard Space Flight Center
HgCdTe	Mercury-Cadmium-Telluride
IFOV	Instantaneous Field of View
InSb	Indium Antimonide
IR	Infrared
MLA	Multiple Linear Array
MRS	Multispectral Resource Sampler
MSS	Multispectral Scanner
NASA	National Aeronautics and Space Administration
PbS	Lead Sulfide
RIU	Remote Input Unit
TM	Thematic Mapper
V.V.	vice versa

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I. INTRODUCTION AND BACKGROUND

An experimental pushbroom scan sensor, called the Multispectral Resource Sampler (MRS) is being developed by NASA for possible earth orbiting spacecraft flight in the mid-1980's. This sensor will provide new and unique earth survey research capabilities beyond those possible with current sensor systems. It was the purpose of this workshop to gather together representatives of the remote sensing research community to make them aware of the capabilities of the MRS concept, to elicit their response about the utility of such a system as a research tool in the various disciplines, and to encourage suggestions for the improvement of the MRS design. This document contains a summary of the presentations and the recommendations of each panel.

The MRS Workshop was held on May 31 and June 1, 1979 at Colorado State University (C.S.U.) in Fort Collins, Colorado. The workshop was opened by Dr. Maxwell of C.S.U., who welcomed the participants. The morning presentations on May 31 were devoted to familiarizing the participants with the MRS system, its history, the technology involved and present system design. Dr. Calabrese, the first speaker, reviewed the history of the MRS in the context of the development of Landsat sensors. (Section 3.1.) Dr. Schnetzler then described the MRS System as it is presently conceived (Section 3.2). Much of the material covered by Dr. Schnetzler appears in the paper, "Multispectral Resource Sampler: An experimental satellite sensor for the mid-1980's" by Schnetzler and Thompson in the proceedings of the SPIE Technical Symposium, May, 1979. This paper is included for reference in Appendix A.

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A summary of the solid state, multiple linear array technology involved in the MRS was provided by Mr. Thompson. (Section 3.3.) A paper covering much of the same material, "Remote Sensing Using Solid State Array Technology," published in Photogrammetric Engineering & Remote Sensing Vol. 45, No. 1., is presented in Appendix B. The morning session was closed with a description of the engineering considerations involved in the design of the MRS by Mr. Meyer. (Section 3.4.)

The afternoon session of May 31 was devoted to presentations by researchers from several disciplines, describing some of the possibilities and implications of the MRS sensor for research. These presentations are briefly summarized in Sections 3.5-3.11. As far as possible the presentation materials are included with the summaries.

The next day the workshop participants were divided into separate panels, according to discipline, to discuss the MRS. At the conclusion of discussions the panel chairmen presented a summary of the panels deliberation. The panel reports are presented in Part II of this report.

The participants of the workshop are listed in enclosure 1.1. The complete agenda of the workshop is shown in enclosure 1.2.

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ENCLOSURE 1.1

MULTISPECTRAL RESOURCE SAMPLER WORKSHOP

May 31 - June 1, 1979

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ENCLOSURE 1.2

MRS WORKSHOP AGENDA

MAY 31, 9 a.m.

OPENING REMARKS — Gene Maxwell, Colorado State U.

INTRODUCTION — Mike Calabrese, NASA Headquarters

THE MULTISPECTRAL RESOURCE SAMPLER (MRS)SENSOR - Charles Schnetzler, NASA/GSFC

COFFEE BREAK

MULTISPECTRAL LINEAR ARRAY (Pushbroom Scan) TECHNOLOGY

BACKGROUND — Les Thompson, NASA/GSFC

SENSOR ENGINEERING CONSIDERATIONS — Bill Meyer, NASA/GSFC

GENERAL DISCUSSION

LUNCH

BIDIRECTIONAL REFLECTANCE STUDIES, AND THE POTENTIAL OF MRS — Jim Smith, CSU

ATMOSPHERIC CORRECTION TECHNIQUES AND THE POTENTIAL OF THE MRS — Bob Turner, Science Applications, Inc.

SPECTRAL FEATURES IN THE 0.4-1.0 um REGION

- GEOLOGY — Graham Hunt, USGS
- VEGETATION — Steve Ungar, NASA/GISS

COFFEE BREAK

SPATIAL RESOLUTION REQUIREMENTS FOR EARTH RESOURCES APPLICATIONS — Lee Miller, Texas A&M

POTENTIAL INFORMATION CONTENT OF POLARIZATION MEASUREMENTS — Bob Walraven, U. of California, Davis

TEMPORAL RESOLUTION REQUIREMENTS FOR EARTH RESOURCES APPLICATIONS — Arch Park, GE

INSTRUCTIONS FOR WORKSHOP SESSIONS — Charles Schnetzler, NASA/GSFC

ENCLOSURE 1.2 (CONT'D)

JUNE 1, 8:30 a.m.

BREAK INTO DISCIPLINE PANELS FOR DETAILED DISCUSSION OF MRS
(8:30 to 2:00 p.m., with break for lunch)

PLENARY SESSION - REPORT BY PANEL CHAIRMEN, WITH DISCUSSION

ADJOURN - Approximately 3:30 p.m.

II. PANEL REPORTS

2.0 INTRODUCTION

During the second day at the workshop, the workshop participants were divided by discipline into eight discipline panels. These panels were each charged with the task of reviewing the utility of the MRS as a research tool for their particular discipline and to recommend modifications to the sensor design which would improve the research capabilities of the MRS. The panels (engineering excepted) were given a set of discussion topics as a guide for the panel discussions. The topics are listed in Table 2.1.

The panel reports are presented below as submitted by the panel chairmen. The discipline groups were:

- Agriculture
- Atmospheric Studies
- Engineering
- Forestry
- Geology
- Hydrology/Oceanography
- Land Use
- Rangeland/Soils.

DISCUSSION TOPICS

1. To enhance its research capability for your discipline, what changes would you recommend in the MRS design?

   e.g. Spectral Filters (Including Polarization)
   Spatial Resolution
   Radiometric sensitivity (Quantization level)
   Swath Width
   Modes
   Pointing angles and speeds.

   (Keep in mind the Technology/Engineering constraints discussed yesterday.)

2. What areas of new research in your discipline cannot be performed with current satellite sensors or the proposed Thematic Mapper? Which of these might be addressable with the MRS as currently configured or with feasible modifications?

3. What Pre-Flight research requires special stress (over next 3 to 5 years) to:

   a. Set sensor design and operation

   b. Insure optimum utilization during flight

   (Be as specific as possible regarding objective, approach and necessary resources)

   e.g. Bidirectional Modeling
   Atmospheric correction tech. development
   On-board data compression methods
   Polarization modeling.

4. What are the benefits of flying the MRS with the Thematic Mapper? What are the impacts of flying the MRS without the Thematic Mapper?

5. Considering a potential data rate change to a 30 megabit per second, would you:

-- want 15 m resolution over a 30 km swath in all 4 bands; or,

-- would you use this added data rate in some other manner?

6. What type of data products should be produced for experimenter/users; and assuming several significant experiments in your discipline, how many scenes would be required per month?

2.1 AGRICULTURAL PANEL

E.T. Kanemasu, Chairman; Marvin Bauer, Eugene Brach, Jerry Hatfield, Claire Hay, Dave Landgrebe, Bob MacDonald, Arch Park, Dave Simonett, Steve Ungar, Jan Cipra

Question 1

To enhance its research capability for your discipline what changes would you recommend in the MRS design?

1.1 Spectral issues

1.1.1 Propose filter change for looking at the GISS red shift (Collins, W. 1978. Photog. Engr. and Rem. Sens. 44: 43-55)--(730-750nm) to (740-760nm).

1.1.1 Propose changing (670-690nm) to (665-685nm) or (660-680nm) to avoid the sharp rise in reflectance near 700nm.

1.1.2 Because there are limited data on the use of polarizers for assessing vegetation type and condition, the panel cannot define the specific polarization filters; however some members of the panel expressed a degree of pessimism about the additional information gained from polarization especially for classification.

1.1.3 Panel emphasizes the need to systematically obtain information on spectral wavelengths and bandwidths before alternative recommendations be made.

1.2 Operating Modes

1.2.1 Recommend 30 MBS.

1.2.2 Desire 30 km swath width.

1.2.3 Selection of 10 bit precision would be based on the impact of atmospheric and other noise on analysis results.

1.3 Spatial issues

1.3.1 15m is acceptable.

Question 2

What areas of research can be addressed by (a) both TM and MRS — (b) with MRS alone?

(a) 2.1 It was the consensus of the panel that MRS should be viewed as an adjunct to TM and not as a competitor or replacement.

2.2 Subsample TM with MRS with greater radiometric and spatial resolution in the areas of crop discrimination and crop condition.

2.3 Classification and crop assessment experiments where TM and MRS are used in concert to assess the effects of increasing spatial, spectral, and temporal resolution and correcting for atmospheric effects.

2.4 Monitor and detect low biomass.

2.5 Relate MSS data utilization to TM and MRS.

(b) 2.6 Bidirectional and stereo experiments such as effects of sun and viewing angles on biomass and leaf area assessment and effects of soil reflectance and plant shadows on scene reflectance.

2.7 Assess crop condition with high temporal, spectral, and spatial resolution.

2.8 Assess crop discrimination with greater radiometric and spatial resolution.

2.9 Assess reflectance effects of dew on vegetal surface.

Question 3

What pre-flight research requires special emphasis?

3.1 Panel emphasizes the need for adequate funds for background research and analysis of data.

3.2 The panel encourages research on other technologies (e.g., lead sulfide, etc.) to make available other spectral regions (mid IR and thermal) as soon as possible.

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3.3 Panel recommends a measurement program with a prototype instrument. Recognizing the high cost associated with a complete aircraft program, a low budget aircraft program would be acceptable.

3.3.1 Bidirectional reflectance research to assess crop condition and discrimination. Some members of the panel emphasized the complex interactions among sun elevation, azimuth angle, view angle, row direction, canopy geometry and wavelength.

3.3.2 Polarization measurements on both the atmosphere and vegetal surfaces.

3.3.3 Data acquisition frequency as a function of crop phenology.

3.4 Ground measurement program

3.4.1 Do 3.3.1 to 3.3.3 with careful selection of platforms.

3.4.2 Experiments should include crop growth and yield models.

3.4.3 Experiments should include agrometeorological observations and expertise.

Question 4

What are the benefits of MRS flying with Landsat D-TM?

4.1 Assess the effect of increased radiometric, spatial, and temporal resolution in the 0.4 and 1.0μm range in crop discrimination and crop condition experiments.

4.2 Use MRS to subsample.

4.3 Possible use of MRS to correct for atmospheric effects.

4.4 Some experiments may utilize longer wavelength data from TM.

What are the impacts of flying without TM?

The panel raised questions in terms of

1) Changing orbit - time of data acquisition
2) Data rate limitations
3) Spectral band selection
4) Dual MRS system for stereo.

Question 5

What type of data products should be produced?

5.1 Timeliness of data - there will be experiments which will require the delivery of data within a few days (3) to a week. For others the requirement could be as long as two weeks or more.

5.2 Experimenter's control - the investigators need the capability to impact the acquisition of data within 2-3 orbits.

5.3 Data processing research - the data are sufficiently more complex than existing data so that we need research in new techniques of handling and processing. On-board compression techniques need to be investigated if limitations in data handling exist.

5.4 Data format - there needs to be the capability to produce raw data but at the same time there needs to be a product that has a common projection (U.T.M.) with minimal radiometric impact such that multitemporal registration becomes possible for most of the investigators. Moreover, the data must be able to be nested hierarchically with TM and MSS.

5.5 Header information - need information, i.e., calibration, geometric distortion, etc., on the header of the CCT which permits the investigator to apply all the necessary corrections.

Question 6

Assuming several significant experiments in your discipline, how many scenes per month would be taken?

Panel could not provide exact numbers but would suggest that Skylab experiments may give reasonable estimates.

2.2 ATMOSPHERIC MEASUREMENTS AND POLARIZATION PANEL

P.N. Slater (Chairman); R.W. Dana, R. Kiang, R.E. Turner, and R. Walraven, panel members.

Atmospheric measurements are proposed for determining corrections of spectral signatures for atmospheric effects and for monitoring atmospheric pollution. Polarization studies are proposed (1) to improve scene contrast by subtraction of atmospheric haze, (2) to discriminate, by differences in their polarizing characteristics, features having very similar spectral signatures, and (3) to identify stress in vegetation by the way it changes the polarizing properties of the vegetation.

The following is a list of the questions discussed in the panel meeting and the resulting answers:

1) What changes would you recommend to the MRS design?

Spectral and polarizing filters. Generally satisfactory but need further study, particularly to find if the 360-400 nm filter can be replaced by a 400-420 nm filter. This would substantially simplify the optical design. The question was raised of tailoring the detector response and optics to match the bands. For example, with the 400-420 nm filter moved to array #1, all filters for that array would be in the blue which would allow for optimizing the antireflection coating of the detectors in that array and also optimizing the focus of that array.

Spatial resolution. 15 m at nadir is about as coarse as we can work with. This corresponds to a pixel about 140m x 38m at $\pm 60^{0}$ to the nadir. For best results, we need to point at a uniform, near-lambertian area several pixels in size. A 10m pixel size at nadir would be preferred.

Radiometric sensitivity. Adequate for atmospheric measurements but 10 bit quantization is highly desirable for polarization work where the difference between two polarized images will be determined. A programmable gain amplifier working in steps of 1x, 2x, 4x, and 8x is also desirable for both polarized and non-polarized measurements.

Swath width. More than adequate for both atmospheric and polarization work.

Modes. 15m/15km is acceptable but 10m/7km is preferred.

Pointing angles. $\pm 60^{o}$ fore and aft, although only one side of nadir may be adequate. $\pm 40^{o}$ across track, but $\pm 8^{o}$ most important to monitor TM scene. Pointing speeds need further discussion pending results of question posed. (Note, the proposed operation of the system for both the atmospheric and polarization studies is briefly as follows: The map coordinates of predetermined sites would be used as input to point the system. An intrack scan covering $\pm 0.15^{o}$ (or 2x pointing accuracy) would be made around each pointing angle to ensure that each site of interest was recorded.)

2) What are the pros and cons of flying with the TM?

We see the MRS as augmenting the TM capability by providing across scene atmospheric correction data. Therefore, if the MTS is not on the same space craft it should be in close orbital proximity to the TM, say within 5 minutes of time and within $\pm$20km of the TM nadir. The TM scene will be useful in locating the small images sampled by the MRS at various pointing angles.

3) What research cannot be performed with the MSS and TM?

The MSS and TM cannot be used for the atmospheric and polarization studies described here.

4) What pre-flight research is required?

In order to exploit the unique capabilities of the MRS in an optimal manner, a number of critical areas need to be addressed in pre-flight research. We believe that the potential of the system for new research in atmospheric physics and polarization phenomena can only be realized by a continuing program involving modeling, and ground and aircraft measurements for the five years prior to flight. The level of effort should, at a minimum, be 6 man years per year or about $450K per year. The following are some of the various research areas that should be addressed:

Modeling work needs to be conducted for atmospheric and polarization studies to determine filter passband positions and bandwidths, angular

sampling intervals, number of quantization levels and desirability of gain control Effects of atmospheric inhomogeneities, BRDF effects, crosstalk introduced by atmospheric scattering, etc., need to be investigated.

Simulation studies need to be continued for atmospheric correction work to determine the desirable accuracy of measurements and the improvement in cross scene and temporal classification accuracy. Specifically for polarization work, there is a need to continue the tower experiments (of Walraven) in conjunction with crop stress measurements. Need to study desirability of a fifth polarization wheel.

A specification needs to be generated, on the basis of lab tests, for the acceptable upper level of sensor induced polarization.

5) How would you use a 30 MbS^{-1} capability?

For atmospheric work we would increase the number of spectral bands. For polarization work, we would increase the quantization to 10 bit, extra bands would probably not be required.

6) What type of data products are desirable?

CCT data and quick look MRS sub scenes (3 x 30km or 3 x 15km) in color to facilitate site identification. TM scenes of same area.

7) How many scenes will be taken per month?

The frequency per site for atmospheric studies should be on days 0, 7, 9, 16, 23, 25...i.e., about 7 per month per site. We anticipate 20 sites from the discipline areas of agriculture, soils, geology, land resources, hydrology, forestry and pollution. The total is about 150 sites per month. For polarization studies, about 7 sites should be monitored about 15 times a month each, over a time interval of 3 months. After this three month intensive study period the frequency and number of sites would be reduced.

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2.3 ENGINEERING PANEL

Members: Stan Addess; Mike Calabrese, Bill Meyer, Chairman; Dave Smith; Leo Steg; Les Thompson

Objective: To examine the implications of potential MRS design changes and additions to the baseline.

1) If 10 meter IFOV is desired, it is felt that there are no technical barriers that would preclude its accomplishment (but not within the baseline constraints).

   Equally within the technical capability are swath width increases limited by the data bandwidth permitted by the system.

2) The entire ground processing activity required to handle MRS data is unique and different from that previously experienced with mechanical scanners. Therefore, it is recommended that early investigation of processing techniques such as retification, temporal registration, atmospheric correction and geometric corrections including resampling be invited.

3) Recommend that dispersion techniques utilizing 2-dimensional detector arrays be investigated as an alternative to the spectral sampling method proposed. This alternative offers flexibility in the choice of number, width and location of the spectral bands.

4) Recommend that the instrument design be pursued to allow the inclusion of bands out to 2.5μm in the event that appropriate detector systems technology becomes available.

5) Since the MRS will be taking multispectral data at high look angles, a study investigating the classifiability of this multispectral data is recommended. Data from the corn blight watch study could be used since multispectral data at high look angles is available in this data set. In addition, spectral data at a variety of look angles is available in the LACIE field measurements data base.

6) The panel endorses the baseline calibration scheme that provides for calibration through the telescope and detector system.

2.4 FORESTRY PANEL

Panel members: Robert Aldrich, G.R. Barker, Norman M. Hatcher, Robert Heller, Roger M. Hoffer, Jim Smith, Darrel Williams, and Lee Miller, Chairman.

Issue I: Recommendations For Changes To Hardware Characteristics

1.1 Spectral Range, Filters and Polarization

1.1.1 Spectral Range. All panel members concurred that a longer spectral range would offer exciting potential applications. The majority also took the stance that a good deal of unexploited potential remains to be examined in the spectral range .4 to 1.0μm with the variety of flexible options and improvements proposed for the MRS device. The narrow range is therefore endorsed as a limit if such a limit clearly ensures an earlier launch by at least two years.

This discipline panel wishes to emphasize strongly that we accept this limit on the satellite device but recommend to all disciplines that any further pre-launch applications research be expanded to include all the longer wavelength range up to at least 2.5 or 3.0μm.

1.1.2 Filter Range and Wavelength Position. The spectral bands required by the general class of forestry experiments anticipated are:

.54 to .56μm (the green peak)
.59 to .61μm (yellow/orange stress)
.67 to .69μm (chlorophyll absorption)
.78 to .80μm (solar IR plateau)

This represents the addition of the .59 to .61μm band to our suite of requirements. It can be supported that this band is sensitive to subtle stress conditions induced in the tree canopy by disease and other pathological conditions, moisture stress, etc. We also recommend that careful consideration be made in

the array positions of two additional bands on other filter wheels as we have secondary interests in using these bands in combination with a specific subset of our basic four. These are the red shift band and the green vegetation/soil cross-over band. These intervals should be positioned so as to interchange with either our green or yellow/orange bands so that either may be used in conjunction with the remaining biomass assessment bands.

The exact width and wavelength position of these bands are not firm and we recommend that additional careful research effort is required to resolve these delicate, fine tuning considerations. Some of the panel expressed an opinion that one or more of our required spectral intervals could even be widened somewhat such as the .59 to .61μm band. Again, this is an issue which should be resolved based upon further re-examination of existing data and further research efforts.

1.1.3 Polarization. The value of multispectral imagery of polarization in forestry applications is simply not known to this panel. Intuition tells us that it may be a source of potential, useful variability which should not be overlooked or omitted. Lack of specific background relative to our discipline prompts us to suggest that all the polarizing filters be placed on a 5th filter wheel so that all bands on the device can be polarized or unpolarized. We recognize that using polarization filters on the narrow 20nm spectral bands may reduce the energy to the detector below that required for a suitable S/N value. We would be willing to review the impact of broadening our spectral bandpass to compensate for this added attenuation. This suggestion for a review of the possibility of a 5th filter wheel also results from the observation that 1/4 of the wavelength positions in the proposed MRS design are currently occupied by polarized broadbands. Thus, one-fourth

of the instruments capability is devoted to observations of characteristics for which we have only very sketchy knowledge relative to their use in connection with vegetative cover.

1.2 Spatial Resolution

This panel sees no particular value in reducing the resolution from 15m to 10m as it would still not resolve any significant portion of our basic scene elements — trees. However, we all recommend that further research be undertaken to quantify the impact of reduced resolution below 15m. A qualitative study of resolution requirements for several hundred forestry applications conducted by the U.S. Forest Service will be issued in a few months which states that a majority of these applications require resolution less than 10m. However, the panel chairman wishes to go on record as unilaterally supporting the request for increased spatial resolution as expressed by the Land Use Panel.

1.3 Radiometric Sensitivity

The proposed 8 bit radiometric resolution was considered adequate by all members.

1.4 Swath Width

Generally speaking forestry targets are of large spatial extent (taken as single units); however, we conclude that since MRS is to be a research device that we can accept the 15 km swath width. A reduction of the swath width below 15 km would not be acceptable for several reasons, including low probability of targeting, sizes of our targets, etc. However, as scientists we also <u>strongly</u> recommend that the swath width <u>not</u> be allowed to increase above 30 km to ensure that the post-launch capability of the device remain available for addressing the many vital research issues for which it was designed.

1.5 Mode Selections

Considerable discussion and disagreement occurred relative to the value of the mode selections and their priority. Our final majority recommendation is that the priority of adding these modes be:

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Mode Priority Order

1) } Considered very important
2)

3) } Of lesser value
4)

1.6 Pointing Angles and Speeds

1.6.1 East/West Pointing. The consensus of opinion was that the recommended maximum pointing angle was adequate. It is more than required for those forestry experiments anticipated which require repeated looks (frequency of coverage) and high probability of a clear sky, single date acquisition in our most critical time frame of two weeks to a month caused insect outbreaks and spring and fall transitions.

1.6.2 North/South Pointing. Again, the recommended north/south pointing angles were felt to be more than adequate for the majority of the forestry experiments envisioned. A strong individual case was made to retain 55^{o} as the upper limit to enable more complex experiments dealing with the bidirectional characteristics of forest cover relative to their value in contributing heretofore unavailable characteristics of the forest canopy. All members felt that the MRS engineering design team should reexamine the slower of the pointing rates and carefully review its impact on the ability of the device to survive a broad variety of experimenter's needs in the continental United States.

Issue II: Increasing The Data Rate From 15 To 30 MBS

The entire panel was in agreement that the additional 15 MBS should be spent in increasing the swath width from 15 km to 30 km and in abandoning the mode selection. We are opposed to expending it in retaining the modes by adjusting them to provide an optional 60 km swath. The panel chairman also notes that since two identical antennas may be used for the 30 MBS rate that a new kind of mode selection may be considered.

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A 15 MBS system to bring down 15 km of data or switch to

A 30 MBS system to bring down 30 km of data.

Thus, a ground station limited to 15 MBS could read out the device whereas moving to a single higher rate transmission would preclude this opportunity.

Issue III: Additional Research Allowed By MRS Beyond The TM

The forestry panel wishes to go on record with clear request that the number of approved funded research experiments be increased substantially above 30. With 30 experiments funded only 2 or 3 would be devoted to a particular discipline whereas any scientist recognizes that experimental redundancy (e.g., related experimental attacks in different competing groups) is the essence of the symbiotic nature of the research process. With that clear statement of our requirements in connection with this research device we offer the following examples of experiments which would be enabled by MRS relative to the TM:

FOREST STRESS DETECTION enabled only by the higher spatial resolution, particular wavelength intervals and narrower bandwidths, and sufficiently high probability of data acquisition in critical 2 or 3 week annual periods.

INDIRECT SENSING OF FOREST STAND CONDITIONS including biomass, morphology, and physionomic attributes enabled by the polarization, steep off-axis pointing, and bidirectional effects.

PLANTATION SEEDLING SURVIVAL AND DEVELOPMENT enabled by higher pointing angles for observing the projection of the smaller, sparse tree cover, bidirectional effects, narrower bands, and spatial resolution.

NORMALIZATION OF TERRAIN INDUCED RADIANCE EFFECTS enabled by simultaneous stereo/multispectral coverage.

MULTISTAGE, MULTITEMPORAL SAMPLING FOR FOREST INVENTORY enabled by increased spatial and temporal resolution and careful spatial multidate registration.

MEASURING CHANGES IN WILDLIFE HABITAT enabled by higher spatial and spectral resolution.

MONITORING CHANGES IN FOREST STANDS enabled by higher spatial, spectral and temporal resolution.

MULTIRESOURCE MONITORING OF FOREST/RANGE/WILDLIFE HABITAT/ WATERSHED CONDITION/ETC. enabled by higher spatial, spectral and temporal resolution.

We conclude this quick list by indicating that it is a hurried set of examples which could be easily added to on further review by us and others practicing remote sensing in our profession.

Issue IV: Data Projects Required

Without specific experimental designs and objectives in mind, this panel was not interested in devoting time to guessing at the data product flow rate, especially in that it appears to be much less than the design capabilities of existing systems required for the related operational satellite sensors. We propose that the emphasis here be placed upon digital products for the prime data source with quick look imagery in black and white and color for site identification, etc. Several applications would benefit from one or two day delivery of the photo products where on-site dynamic conditions can be pinpointed by defining the exact field sites covered immediately after image acquisition.

All members agreed that as much of the common processing should be achieved at one common location and that such a location (or several locations) also function as a support facility to which the individual experimenter journeys for more specific processing. However, we would still wish to retain the option of stripping off the digital data to tape to take to our specific institutions for in-depth treatment.

Issue V: Same Satellite Vehicle As TM Or Not

Our general conclusion was that many types of experiments could be conducted if MRS was not on the TM vehicle; however, an additional class of experiments would be enabled by obtaining boresighted data from MRS and TM. We saw no particular handicaps from being onboard the same vehicle as the TM.

Issue VI: Recommended Pre-Flight Research

The following is our offering of possible pre-flight research efforts. Insufficient time was available to indicate their relative importance.

6.1 Polarization

Determine if there are any polarization effects introduced by the linearity of the detector scan.

Determine feasibility of adding fifth polarization wheel.

Assess what we can expect in forestry from polarization measurements.

6.2 Sampling

Design sampling strategies which will optimize MRS capabilities in its forestry applications.

6.3 Spatial Characteristics

Measure the value of the increased spatial resolution.

Carefully evaluate the spatial registration that can be achieved with the off-axis pointing.

6.4 Spectral Characteristics

Accurately determine bandwidth and locations particularly for the yellow/orange "stress band".

6.5 Bidirectional Characteristics

Conduct bidirectional studies of stand structure.

6.6 Queuing

Develop queuing algorithm to determine how many experiments and experimenters can be serviced in the U.S. with the design capabilities of this device.

Develop computer queuing algorithm to determine who gets what in a multimode satellite with continous conflicts between a variety of experimental requirements.

2.5 GEOLOGY PANEL

Members: D.P. Gold, Chairman; M. Abrams, W. Collins, G. Hunt, D. Levandowski, K. Meehan, F. Sabins, R. Black (part-time).

The core of the geology committee consisted of seven persons. Robert Black, a geologist, shared his time between the geology panel and the hydrology/oceanography group.

Abstract

The geology panel began on a somewhat negative note because the limited spectral range and the short wavelength capability of the detector had little to offer in geological applications investigating bedrock composition and structural characteristics. In addition, one member voiced concern that the untried system would be launched without adequate ground simulation and aircraft overflight testing of the concepts. Another member, with previous experience on panels such as these, expressed concern that we were being asked to "give blessing" to a system already frozen in concept and design.

The conceptual design and constraints of the MRS were acceptable, except for the limited number of simultaneously imaging bands (4), which severely restricted the discrimination from spectral curves of certain materials (rocks and soils) and stress conditions in vegetation. This panel strongly recommends designing at least two addition channels into the system and we would like to go on record with a plea for detectors capable of imaging in the longer (IR) wavelengths. The concerns of the panel were that more work was needed on selection of the bands, bandwidths and filter wavelength and their positioning on the discs. Some of the necessary background data are currently available in raw form, but that additional experiments were needed to help in the selection and testing of the filter combinations, wavelength, bandwidths, etc.

The group warmed to the subject as additional geologic applications became apparent, and the meeting ended on a positive note (at least enthusiastic if not a fully-shared optimism). In summary, we stress the need for adequate funds for research in the optimum filter, wavelength and panel widths and pre-launch testing of the concept, and we make an earnest plea for an engineering review into increasing the number of detectors to six (6).

Specific Questions

1. Possible Design Changes

We see the current specifications as a practical compromise of multi-disciplinary needs, with a relatively limited application to conventional geological problems, but with scope for innovative tasks. There are likely to be modifications to filters, filter positions, bandwidth and wavelength, etc., as work in these areas progresses (pre-flight research on these is crucial to the ultimate success of this mission). A 15m resolution, 8 bit data, 30 km to 15 km swath width, and the pointing angles are acceptable. The most useful design change would be to six (6) simultaneous channels, and would also mean a modification of the mode. We also urge NASA to examine the possible inclusion of a detector array in the 1.6 and 2-2.5μm region.

2. Improved Data Rate (15 M bits → 30 M bits/sec)

We recommend using this additional capacity to:

a) Add at least 2 additional channels;

b) Fly a narrower swath width, i.e., 15 km with all detectors operating.

3. Research Advantage

We see the narrow wave band capability, the high signal to noise ratio, and the pointability as the main attributes of the MRS system. The major advantage of this multichannel, narrow wave band system to geologists would be for:

a) Biogeochemical and geobotanical applications (mainly in the .59 to .61, and .73 to .78 μm range*). However, at least 6 channels would be necessary to adequately categorize the discriminating parts of the spectral curves of stressed vegetation.

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* Wavelength and bandwidth are estimates to be revised after future research.

b) Lithologic mapping for specific iron oxides and hydroxides in rocks (particularly alteration halos around certain ore deposits) and soils (0.40 to 0.42, and 0.84 to 0.9 μm)*. The success of discriminating specific spectral signatures lies in increasing the number of channels and decreasing the bandwidth.

c) The pointing ability would give an improved temporal coverage so necessary for studying rates, e.g., the effects of natural disasters (earthquakes, landslides, volcanoes, floods and hurricanes), and other dynamic earth processes (coastal erosion and deposition, delta formation and "galloping" glaciers).

d) The pointing ability would enable one to study land forms, physiography and morphotectronics from images in a stereo model.

e) Derivation of unknown spectral information linked to polarization effects.

4. Pre-Flight Research

The panel stressed the need for adequate funding for pre-launch research and testing. They recommend that programs be initiated to:

a) Perform library research and basic experiments to establish optimum bands and bandwidths;

b) Erect an aircraft flight program to test effectiveness of the bands selected and the equipment over test areas, and to ensure that calibration problems are solved;

c) Improve performance in data compression and onboard data processing.

5. Benefit of Flying with Thematic Mapper

The panel concludes that a mated flight with the thematic mapper is desirable because:

*Wavelength and bandwidth are estimates to be revised after future research.

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a) TM imagery could be used for locating the MRS targets for small targets off NADIR.

b) The MRS would complement the TM by giving greater resolution and "special effect" coverage of any anomalous objects or effects identified on the TM imagery.

c) The TM image may be able to provide a base line geometry for geometric correction of dissected "oblique" MRS pixels.

d) Provide at least two different scales of data from the same area.

The panel recommends that an altimeter be added to the spacecraft for use in geometric corrections and in snowpack measurements.

6. Data Products

As a research tool the panel does not see the necessity of a wide range of paper products. They would like to have the data available quickly in:

a) Raw digital form (CCT tape) with leaders on calibration, geometry, ephemeral information, etc., and a limited range of "quick" turnabout prints.

b) A timely data turnaround of about two weeks on a routine basis -- faster for specific experiments or dynamic events.

c) Easy access of data for other users.

d) Provision during operation for "targets of opportunity" by the scientific community.

e) A running compilation of data available and what has been done with it. Scenes should be annotated with necessary flight, orbital, etc., parameters and include some comment on the quality.

f) The special "stereo" targets should be processed to produce good quality prints.

2.6 HYDROLOGY/OCEANOGRAPHY/COASTAL ZONE PANEL

Panel Members: Jack Hill, Chairman; Dave Bowker, Bill Philpot, Larry Fisher, Robert Black.

1. To enhance research in hydrology/oceanography, what changes are recommended in the MRS?

a) Spectral filters:

1) Expand blue - change 400-420nm to 430-450nm (for chlorophyll and bathemetry).

MOCS (Langley) data indicates that for chlorophyll detection:

- 475nm represents maximum absorption (this channel is not presently represented in the proposed MRS channels and no MRS channels are near this region).
- 537nm represents crossover (this channel is also not represented in the MRS selection, but the proposed 540-560nm channel could be changed to 530-550nm).
- 678nm represents maximum absorption (this channel is represented in the MRS selection).

2) Possibly expand IR from 930-950nm to 800-950 (1000) nm or add a new filter (for better land/water boundaries and surface H_2O information).

3) 580-620nm would optimize the detection and monitoring of acid dumps, but these dumps can be observed in the proposed red and green channels.

4) 780-820nm would optimize the detection and monitoring of sewage dumps; the MRS channel from 780-800nm may be sufficient.

b) Stereo work at this resolution 15m is not of benefit to ocean physics (i.e., wave height, direction).

c) Polarizing filters on a fifth wheel should be considered, may want to polarize TM1 and 2 instead of TM3 and 4, as well as V and H in the blue. While it is not clear whether the following channels were vertically or horizontally polarized, the literature indicates that for oil detection and monitoring:

- 360-400nm is a good visible range channel, but it also presents atmospheric interferences (this is a proposed MRS channel).
- 410-430nm is satisfactory (a MRS channel presently exists--400-420nm), but if it is changed to 430-450nm there may be some overlap, but not positively.
- 555-575nm represents a minimum response (a channel in this region is not necessarily a critical need).
- 760-780nm represents a maximum response; there is not a proposed MRS channel in this region, but between TM4 and 360-400nm oil may be sufficiently detected.

d) Pointing angles - MRS must be registered to the TM image - will need wider angles to study slicks, oil, internal waves, etc.

e) Must be overlayed on standardized grid — a must for temporal studies.

f) Improve radiometric sensitivity by increasing the detector integration time. The spatial resolution could be reduced to as much as 60m and still be useful for many water investigations (i.e., lakes, estuaries, open ocean).

g) 15m is acceptable in most cases, 60m or more is sufficent in open ocean.

h) Two-day coverage is satisfactory, but not so good for tidal patterns, pollution, dynamic processes, etc.

2. Is it of benefit to have 30km swath width with 15m resolution in all four bands or would it be better to use the increased power in some other manner?

- Keep with the 15 megabit machine, with 4 proposed modes, this stops some data handling problems during analyses stages.

3. What areas of new research in your discipline cannot be performed with current sensors or the TM? Which of these might be addressable with the MRS as currently configured or with feasible modifications?

<u>Greatest benefit</u> is high repetition rate for transient events?

--Wetland/mudflat mapping
--Rivers can now be monitored
--Urban hydrology (runoff and impervious areas)
--Frontal systems
--Hydrologic modification
--Bathemetry
--TM - snow mapping over large regions
MRS - snow mapping in small basins
--Ice movement
a. Fractures in ice
b. Spring thaw and ship routing, iceberg formation
--Inland water body inventories and eutrophication studies
--Regulatory possibilities -- 200 mile limit, hazardous material spills, dump sites
--Disaster events.

4. What <u>pre-flight</u> research requires special stress (over next 3 to 5 years)?

a) Water quality study using an aircraft-mounted scanner to test the utility of the chosen filters. These studies should also vary bandwidths and center wavelengths, all of these studies should be conducted over standard study sites.

b) Polarization and angular studies, especially in blue, possibly on existing breadboard system.

c) More complete survey of oceanographic literature and research/user community.

d) Incorporate data obtained for a) and b) into standard format for use by rest of remote sensing research community.

e) Test feasibility and organization of real-time capabilities; dynamic and catastrophic events.

f) Atmospheric correction developments and polarization modeling.

g) Test a similar system on shuttle at first opportunity to see similar data, over any areas.

h) Number of researchers should be more than 30 — possibly 50 and there should be a secondary hierarchy of universities and agencies that could coordinate and process some of these data. No one should be shut off from acquiring data, everyone should be able to acquire satellite data. For any given target, all possible researchers should be notified so that they too have the opportunity to acquire their particular surface truth. The experimenter's only priority is his surface truth, never the satellite data.

i) Look at longer along track integration times — possibly incorporate selectable clock time changes into satellite — could be easy task.

j) Look at same target over numerous angles through the full plus to full minus 55 degrees.

k) Research costs must exceed hardware costs, both during pre- and post-flight periods.

5. What is the impact of flying without the Thematic Mapper?

Actually need TM:

a) A must for shelf and open ocean work. TM would be better than MRS in these areas.

b) Use TM for large area referencing and study and MRS for sampling (spills, fronts, etc.).

c) If MRS flies by itself, still need a large scale imager (even if one band) — MRS type system should be considered on next AOCS (Advanced Ocean Color Scanner) or next OCS (these have wide views of ocean areas).

6. What type of data products should be produced for the experimenters? Assuming several significant experiments in your discipline, how many scenes will be taken/month/year?

Two levels of processing:

a) Simple calibration, digitized (CCT), useable standard format (Landsat) and quicklook (real-real-time) product (print) — no enhancement, georeferencing, atmospheric corrections.

b) Calibrated, georeferenced, atmospherically corrected, CCT with appropriate header data, correction software to user groups, and a document of exactly what has been done to these data from reception to the time the user receives it.

c) Grossly estimated number of scenes:

--Glaciers and river and lake ice flows: 30/year per area

--1 time-state inventory (with update every several years) ±200/state

--Regional Planning (Urban Studies) 15/year per state 1500/year

--Estuaries (tidally dominated) need to monitor, high/low tide, max. ebb and flow tides, and shoreline/estuary changes (6 every month, 72/year)

--Entire tidal cycle (every other day; 1 estuary) 180/year

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--Marshes (wetland mapping, vegetation mapping, tidal heights, submerged aquatics) (season, 5 per/season) 20/year

--Oceanography
Regulatory (200 mile limit, pollution) (every 2 days) 180/year

--Crises (fish kills, floods, redtides, oilspills and damage assessment of storms) and prediction of crises (earthquakes, volcanoes, etc.) 100/year

--Fisheries (upwelling, etc.) (1 test site) 10-15/year

--Water quality (algae blooms, lakes, coastal zone, open ocean) 100/year

--Land/Water - Cause/Effect Studies (208 pollution oriented projects) 50/year

In actuality, just keep taking the pictures until we get a good one!

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2.7 LAND RESOURCES PANEL

Panel Members: John Estes, Chairman; Jerrold Christenson, Robin Welch, Leonard Gaydos, Armond T. Joyce, John C. Antenucci, Richard Ellefsen, Carol Riordan, Charles Walthall.

Section I	Recommendations
Section II	Background
Section III	MRS Design Changes
Section IV	Needs for Increased Data Rate
Section V	Areas of Research
Section VI	Pre-flight Investigation
Section VII	Benefits of Joint MRS and TM Mission
Section VIII	Experimenter Data Products

I. Summary Of Significant Land Resources Panel Recommendations

The following significant recommendations of the Land Resources Panel are drawn from the text contained in the body of the report. For more detail regarding the background to specific recommendations the reader is referred to the body of the Panel's report.

- The Panel feels that the optimum resolution for Land Resources investigations employing an MRS type instrument is on the order of 3-5 meters. This high resolution would permit investigators/users to address a number of level two and three land use/land cover mapping tasks beyond the correct capabilities of lower resolution satellite systems. In addition a number of important vegetation and rural urban change phenomena may be more adequately studied employing this higher resolution data. The panel feels most strongly that NASA should research the issue of optimal resolution more fully.
- Considering the system modes of operation presented to the Panel for comment and recognizing the difficulties inherent in the above recommendation, the Panel strongly recommends

the following as an acceptable alternative: 15 m resolution/ 30 kilometer swath for all 4 bands of MRS data. This option requires the use of the 30 megabit data rate option.

- The Panel supports the inclusion of the Thematic Mapper bands in the MRS filter arrays.
- We recommend the addition of one band in the blue (.440-.460) portion of the EM spectrum and the shifting of the .490-.510 band to .480-.500 to more adequately discriminate urban targets. We also would like to see a band in the .590-.610 range for vegetation analysis.
- The Panel feels the case for polarized data requires more research. We support the recommendation for the addition of a filter wheel solely for the purpose of providing polarized data (the "5th" wheel). If this is not deemed practical from an engineering standpoint, we recommend that no more than three filter positions be allocated to the production of polarized data.
- The Panel strongly recommends that a good deal of research be directed in the near term toward determining the optimum spectral bands for the detection of Land Resources Parameters.
- The Panel feels that for many applications/experiments 6 or 7 bit data might be sufficient. The Panel feels that the need for 8 bit data should be investigated for Land Resources.
- The Panel feels that the MRS swath width should be no more than 30 km. That a single mode (15m/30km/30 megabit) or at most 2 modes should be operated and that currently proposed pointing capabilities are adequate for Land Resources Investigations.
- The Panel feels most strongly that information sufficient for geometric correction to a number of coordinate grid

systems be included in the header of the computer compatible tapes of MRS data and that hard copy products be corrected and annotated with appropriate tick marks.

- The Panel strongly recommends that the MRS fly with the Thematic Mapper. This will allow Land Resources Researchers to investigate a number of critical issues related to spatial resolutions and registration of multispectral, multitemporal, variable format data.

- Finally, the Panel recommends most strongly that the pre- and post-launch experiment program to be conducted testing the full potential of the MRS system be given adequate financial support by NASA. The Panel feels that on the order of 15% of the total systems cost should be put into research on applications of the system and that this money be protected from use to cover cost over-runs in other areas of the program. This community cannot stress enough the need to adequately support investigations.

II. Background

Within the context of this study Land Resources considered to cover those major research applications areas currently being discussed in NASA's developing Remote Sensing Land Resources Research Plan. These research/applications areas include:

- The production of accurate Land Use/Land Cover classification map type products with accompanying statistics from remotely sensed and collateral data;

- The ability to input these data into geographic or georeferenced information systems and have them effectively interact with other socio-economic and bio-physical information;

- The ability to employ remotely sensed and ancillary data to detect changes in major land use/land cover parameters in an accurate and efficient manner; and

- Employing remotely sensed and other data in modeling land capability, suitability parameters and to employ these data in a predictive fashion.

In addition to these major generic research areas, Land Resource Panel members felt that it is important to study environmental hazard and quality parameters, e.g., flood mapping, earthquake or hurricane damage, effects of strip mining, etc. With these topic areas in mind and with the background of the one day of MRS systems and environmental effects briefings, the Panel set out to answer the following questions:

- To enhance its research capability for your discipline, what changes would you recommend in the MRS design?
- What areas of research in your discipline cannot be performed with current satellite sensors or the proposed Thematic Mapper?
- Which of the above research tasks might be addressable with the MRS as currently configured or with feasible modifications?
- Considering a potential for a 30 megabit data rate would you:
  - -- Want 15m resolution over a 30km swath in all 4' bands; or
  - -- Would you use this power in some other manner?
- What "Pre-Flight" research requires special stress (over the next 3 to 5 years)?
- What are the benefits of flying the MRS with the Thematic Mapper?
- What are the impacts of flying the MRS without the Thematic Mapper?
- What type of data products should be produced for experimenters/users; and

- Assuming several significant experiments in Land Resources, how many scenes would be required per month?

To accomplish the task of discussing and answering the above in the limited time available (approximately 6 hours including lunch) each Panel member was assigned the responsibility for taking notes on and framing the draft answer to one or more of the questions listed above.

III. MRS Design Changes

To enhance its research capability for your discipline, what changes would you recommend in the MRS design, e.g., spectral filters (including polarization), spatial resolution, radiometric sensitivity (quantization level) swath width, modes pointing angles and speeds?

Within the context of this question the Land Resources Panel held lengthy discussions on two very important topic areas. The first was the configuration of the spectral filters and associated polarization. The second area was spatial resolution. Discussion of other design parameters received somewhat less attention within the time allotted to address these questions as Panel members generally felt that the spectral and spatial parameters (temporal or frequency of coverage being considered very satisfactory) should command most of our attention.

Both areas were reviewed in the context of the "straw man" concept with the following conclusions:

a) That the Thematic Mapper bands 1, 2, 3, 4 in filter position one should remain intact;

b) That filter positions two and three should remain unaltered;

c) That filter positions four and five be rearranged in location and spectral region to read as follows:

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Array No.

	1	2	3	4
F.P. 4	360-400 nm	*480-500	930-950	*590-610
F.P. 5	**TM4	**TM4	**TM3	*440-460
	Vert.	Horz.	Vert.	

The Panel reviewed several suggested polarizing configurations. The conclusions were to support an independent fifth polarizing filter wheel which can be rotated through a 360^{0} phase shift. This approach would provide maximum opportunity for spectral polarization while minimizing the problems of space craft and target alignment. A second, less desirable configuration would be the elimination of the polarizing element of TM 3 Vert. in F.P. 4, A. No. 2 and TM 2 Horz. in F.P. 5, A. No. 3. Position 5, No. 1, 2, 3 would have TM 4 Vert., TM 4 Horz., TM 3 Vert. respectively. In general it can be said that the addition of the .440-.460 band and the shifting from .490-.510 to .480-.500 and changes in filter wheel positions are to provide better discrimination of interurban spectral signatures. These changes are based on our analysis of the limited spectral literature on such topics and largely on the work of Root and Miller, 1971, "Identification of Urban Watershed Units Using Remote Multispectral Sensing," Completion Series Report No. 29, Colorado State University, Fort Collins, Colorado (see pages 50 and 51).

The addition of filter 4 in array 4 the .590-.610 band was felt desirable based largely on the comment brought up during the meeting by Bob Heller, a forester from Idaho State University, that this was an important region for the detection of stress in vegetation. The location is such that it picks up the "red shift" which has been found to accompany stress conditions in certain types of vegetation.

* Changed.

** If required.

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Spatial resolution was identified as the single most important characteristic in the MRS configuration for land resources applications. The Panel has identified significant mapping needs that will require spatial resolution of 3-5 meters (see Section V). In light of the importance of this point, the Panel feels that the concept of this ultrahigh resolution demands additional study. Even a cursory examination of the limited number of significant research topics which could be listed in the short time frame allotted for this discussion will indicate the need to explore this topic further. The Panel feels strongly that because of the nature of land resources requirements, particularly the need to accurately map categories of environmental information in regions of high spatial frequency of change in categories, more research should be directed here. This is particularly true when one realizes the need for "pure" pixels and examines the degradation in effective instantaneous field of view (EIFOV) resulting from the need to overlay accurate high resolution pixels from more than one date to improve classification accuracies. Should funds for research in this area not be available several Panel members expressed a willingness to attend and a desire for a future meeting to specifically address this important topic. Finally, it is important to remember that in the digital domain high resolution data can be aggregated to lower resolution pixels with limited difficulty; however, the reverse is definitely not the case. Realizing, however, both from an engineering and programmatic standpoint the difficulties in achieving high resolution on the currently proposed MRS, the Panel considers that an acceptable alternative to be 15m resolution, 30km swath width with all four TM spectral bands. This option requires a 30 megabit data rate. The Land Resources Panel feels strongly that significant land resources research and application as seen from Section D of this text (an again admitted short list due to time constraints) can be accomplished employing this configuration. We strongly urge this configuration be the primary operational mode of the proposed MRS sensor system.

With respect to the number of quantization levels the Panel feels that 8 bit data are certainly sufficient for the majority of Land Resources applications at this time. We feel, however, that if the possibility for improved resolution, in fact, does exist, an engineering study should be

accomplished to determine if going from 8 to 7 or 6 bit data would significantly aid this cause. The Panel feels thet spatial resolution to be of more value than the larger number of quantization levels. The Panel does stress, however, that no less than 6 bit and preferably 7 bit data be maintained at the minimum.

In terms of swath width the Panel stands ready to sacrifice swath width for resolution also down to a minimum 10 km and preferably 15 km swath. We feel that a 30 km swath is optimal and recommend that this be adopted. We see no need at this time for larger swath data. Most urbanized areas of the world will fit into a 30 km swath and indeed into a 15 km swath. This factor facilitates both the urban and rural urban fringe areas of applications research in the land resources area. In addition with the use of appropriate test sites and sampling designs the Panel feels that significant demonstrations of applications capabilities could be made to the majority of land resource research areas with either the 15 km or 30 km swath configurations.

As discussed above, the Land Resources Panel sees little need for a number of modes of operations on MRS and most strongly recommends, if the high resolution option is not available, that a single mode 15 m resolution 4 band 30 km swath width option in the "straw man" document be the mode chosen. The Panel also feels that the pointing capability discussed in the straw man document is adequate for land resource investigations with the caveat that the speed of changing pointing angles be examined to determine its impact on potential test site selection.

IV. Increased Data Rate

Considering the opportunity for a 30 megabit data rate (as opposed to 15 megabit) would you:

a) Like to see a 30km swath with 15m resolution in all four bands

b) Would you use this power some other way?

The Land Resources Panel strongly supports a 30 megabit data rate for the MRS. This data rate effects the options for greater resolution and swath widths that the Land Resources Panel recommends, namely a 3-5 meter resolution

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with a swath width of no less than 10 km. Given a 30 megabit data rate the Panel has also recommended additional research on the potential for reducing from 8 to 6 or 7 bits the data quantization for each sensor to support increased resolution while maintaining swath width. Should the production of higher resolution data be impractical owing to engineering or programmatic considerations the Panel strongly urges the use of the 30 megabit data rate to provide data as described in option A above, i.e., a 30 km swath with 15 m resolution in all 4 spectral bands.

V. Areas Of Research Which Cannot Be Performed With Current Satellite Sensors or Proposed Thematic Mapper

Although possibilities for new experiments are dependent on advances in all three forms of resolution--spectral, temporal and spatial--the primary concern of the Land Resources Panel was what could be done with improved spatial resolution. Agreement on this led to a further question of what could be achieved with yet higher spatial resolution than the 15 meters proposed in the "straw man" MRS documents, something on the order of 3 to 5 meters. Accordingly, the following list of possible experiments is grouped into the two classes: 1) those experiments in which 15 meter resolution is acceptable and is, indeed, a quantum improvement over Landsat or the proposed TM data; and 2) those experiments which would require even higher resolution, probably in the 3 to 5 m range.

The locale for land resources studies comprises both urban and rural areas but the former receives the greater emphasis in part owing to the inherent smaller size of surface features and in part because of the largely rural focus of other discipline panels, agriculture, forestry, range and the need for urban studies in today's world.

A quick and by no means complete listing of possible land resources experiments which could be conducted with 15 meter data (and not as well with TM 30 m data) are:

A. Typing areas within the urbanized boundary (the contiguously

built-up city) and identifying and quantifying urban features at the periphery:

1) Change detection and urban growth monitoring:

2) Identification, analysis and measurement of all types of open spaces (parks, ag. land, land in transition, etc.);

3) The spatial arrangements of buildings--distance apart, size, etc.;

4) Identification of vacant land within the urbanized area which could be developed (especially important today with the need to "in-fill" rather than sprawl);

5) Monitoring expansion of urban periphery as input to improving urban growth models.

B. Beyond urbanized area boundaries:

1) Improving relationship with ancillary data in geo-based information systems;

2) Monitoring of land conversions such as strip mining; and

3) Detection of the presence of small urban outliers.

Again an admittedly incomplete list of possible land resources experiments which require resolution higher than 15 meters are:

A. Within the urbanized area:

1) Considering that the data are spectral and as such are providing information on the physical characteristics of objects, the possibility is open for relating this physical information to physical problems (morphological characteristics rather than inferred functional) such as:

a) Determination of the types and amounts of impervious surfaces for interaction in water; quality studies (e.g., "208" studies);

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b) Determining orientation of buildings to evaluate possibilities for passive solar radiation;

c) To determine the stages of conversion of agricultural land to urban ("stress") indicators as response to urban pressures at the city's periphery;

d) To perform demographic studies such as school population forecasts, tax-base;

e) To evaluate several aspects of measuring land use quality, e.g., housing, vacant land;

f) To make five evaluations of vacant land for development purposes;

g) Converting what are now (Landsat and TM) linear features and making real features out of them — that is transportation features such as streets;

h) Experiment with land use features as they interact with U.S. Census Block Housing data.

In interfacing ancillary data with the higher resolution information the move to resolutions higher than 15 meters should facilitate the use of block level rather than tract level census data. It should also improve our ability to detect changes at a more discrete level of aggregation.

B. Experiment in areas lying beyond the urbanized boundary

1) Mapping at more desirable levels than is now possible (either Level II or III). Examples are:

a) Pastural/rangeland distinction;

b) Woodland/orchard distinction; and

c) Cropland/pasure distinction.

In brief again, for some other possible experiments it is not possible to evaluate whether more or less than 15 m resolution is required. Examples are:

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1) General improvement of classification of urban features through use of texture and contextual data;

2) Improvement in relating all land use/land cover data with ancillary information in geographic-based information systems;

3) Damage assessment — flood, earthquakes, etc.

Again the Panel recognizes that the above listings are by no means complete and represent the best judgment of the panel at this time. We strongly recommend that an experiment be conducted to document the case for optimum resolutions for achieving accurate classification of land resources information.

VI. Pre-Flight Investigations

The Panel recommends that pre-flight investigations be initiated in the following areas:

1) Polarization Applications

a) Separate filter wheel permitting polarization with any filter pack. (Rotatable polarizing); and

b) What advantages can be gained in land resource analysis by use of polarization?

2) Higher Resolution

a) Justification for higher resolution than 15 m; and,

b) Trade-offs in collecting high resolution data from aircraft versus spacecraft?

3) On-board data compression

a) Advantages and limitations of on-board data compression from a land resources classification accuracy perspective; and,

b) Can data be compressed in areas of essential homogeneous land resources classes and what is the impact of this compression on mapping and statistical accuracies?

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4) Pointing angle speeds

   a) What loss in data can be expected during time pointing angles are being changed?

5) Modeling

   a) Investigate 4 areas listed on "straw man" questionniare, i.e., bidirectional modeling; atmospheric correction technique development; onboard data compression methods; and, polarization modeling.

   b) Spatial resolution for various levels of regional, local, and textural questions?

6) Temporal domain and temporal resolution

   a) Change detection;

   b) Land resource analysis;

   c) Land use calendar.

7) Quantization levels

   a) Advantages and limitations of 256, 128 and 64 levels?

8) Registration

   a) MRS and TM at NADIR;

   b) MRS and TM off-axis;

   c) 2 cell size;

   d) Multidate;

   e) Hisforic MSS?

9) Spectral bands

   a) Optimum bands from MRS list;

   b) Optimum arrangement from MRS list;

   c) Polarization filters removed and replaced by rotatable polarizing wheel that will cover all filter groups or more;

   d) Changes in filter spectral characteristics;

e) Advantages and limitations of narrow bands (20nm) for land resources.

The Panel feels these are all important topics which demand research. Although time constraints precluded rigorous prioritization we recommend studies be initiated on these topics as soon as practical.

VII. MRS/TM Relationship

What are the benefits of flying MRS with TM and what are the impacts of MRS without TM?

By flying the MRS with the TM we have a tremendous opportunity for examining the actual effects of higher spatial resolution, holding spectral resolution and atmosphere constant. We can use this ability to examine the effects of differing spatial resolutions in varying environments and compile recommendations for optimal operational spatial resolutions for examining various land resources problems in areas of differing landscape complexity. We can do similar studies of the effects of varying the spectral resolutions.

We will be able to register MRS with TM data much better than if they were not flown together. By having MRS flown with the TM we can evaluate off-angle MRS effects using TM as a base. This will be quite important in looking at signature extension possibilities.

Without the MRS and TM flying together we would miss these opportunities and have a major problem of registering MRS with TM data. We see no reason not to fly both together but many reasons for flying them both on the same satellite; therefore, it is the strong recommendation of the Land Resources Panel that the MRS and the TM both be flown on the same platform.

VIII. Data Products

The Land Resources Panel feels that in the area of data products the following types of processed MRS data should be made routinely available to experimenters/users by NASA or some other appropriate organization:

-- Computer compatible tapes (CCT) and high density digital tapes (HDDT) which have been radiometrically corrected and contain information on image geometry sufficient to facilitate geometric correction to, at a minimum; universal transverse mercator (UTM), space oblique mercator (SOM),

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state plane coordinate (SPC) and longitude-latitude coordinate grid systems (LL).

-- 9" x 9" 70mm and 16mm panchromatic and color combined positive transparencies and prints as well as negative image products with appropriate annotations similar to those on current Landsat images of individual MRS band acquired of a given scene. These data should be both radiometrically corrected and formatted to one of the coordinate grid systems listed above (UTM, SOM, SPC, LL) and annotated with appropriate tick marks as requested by the experimenter/user.

Although difficult to project, the Panel feels that it is reasonable to assume that domestic land resources experiments will require a minimum of 300 scenes per month (60 areas x 5 scenes per month). We feel that a large number of foreign investigators in the land resources area will request data. Again, though difficult to project, we feel foreign demand would be on the order of 300 scenes per month.

Recommend another meeting to lay out research design.

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2.8 RANGE/SOILS PANEL

Panel Members: Gary Peterson, Chairman; Jan Cipra, Don Deering, Bob Haas, Cliff Harlan, Gene Maxwell, Don Moore, R.J. Murray, Paul Seevers.

I. <u>Changes in MRS Design</u>

Spatial Resolution -- No great improvement going from 15 meters to 10 meters. Even at 15 meters often get mixed pixels. If use computer analysis, maybe 15 meters is optimal because of increased computer costs at greater resolution.

Spectral filters -- In general, the proposed spectral filters are adequate. We should look at narrow spectral bands on the orange-red region to determine if this region is useful for plant stress investigations.

710-730 nm band should be studied to determine if it should be replaced by some other band. Polarization is a very good experiment - it may be helpful in species identification.

Polarized band around 420-470 nm could be useful for senescent vegetation/bare soil determinations.

Polarization may also be useful in soil roughness studies.

Have to be careful as there is some polarization in the optics.

Stereo data -- should be extremely useful data for landform analysis and for determining drainage patterns.

Much of range production is related to soils, especially depth of soils. Inferences about soil depth may be possible from slope determinations.

Swath width -- 15 or 30 km swath widths are adequate. More flexibility in filters or resolution is more important than increased swath width.

Satellite must be stable to allow repeat coverage over study sites.

There should be a locator system on the satellite to allow the investigator to accurately locate pixels, or just study sites, on the ground. This is especially important for off-nadir look angles. Maybe reflector devices

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could be used to help locate pixels. To know what on the ground gives a certain reflectance, we need to know our location within 1/2 pixel. Pixels need to be located if (1) we need to know radiance from a specific area; (2) an experiment is trying to assess the benefits of 15 m resolution; (3) attempts are made to register data when viewed from off-nadir.

Modes -- Mode 1 would appear to be the most acceptable.

Radiometric sensitivity -- Eight or ten bit.

Pointing angles and speeds -- adequate as designed. Pointing capability will help by pointing in an anti-solar direction to reduce shadow effects. Observation of landforms under different illuminations should be useful in landform analysis.

II. How Would You Use Increased Data Rate?

Addition of more spectral bands more important than increasing swath width.

Maybe part of the data stream could be used for locational information.

III. Areas of Research Addressable With MRS

Narrow band passes may allow for better identification of soil - vegetation delineations (natural soil groupings). This would include the introduction of the stereo model use as a subsampling system for multi-stage sampling.

Improved spatial resolution --

1) May be possible to map vegetated range sites

2) Map brush density

3) Map wildlife habitat

4) Identify critical areas, such as erosion hazard areas

5) May get improvement in biomass estimates.

Improved spectral resolution --

1) Improved green biomass estimates

2) Identify some plant communities

3) Plant stress detection.

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Multi-temporal --

1) Important in monitoring changes in range condition, and vegetation and soil trends.

IV. Pre-Flight Research

Panel felt strongly that well supported pre-flight research was essential to the success of MRS. The Panel also felt strongly that adequate funds be made available for research on the MRS data.

The following pre-flight investigations were discussed:

1) Refine spectral bands
2) Effects of changing view angle on detection of green biomass, dry biomass, soils and soil/vegetation mixtures
3) Determination of amount of cover by looking at oblique and nadir angles
4) Accuracy location and registration needs and methods of meeting needs should be determined
5) Atmospheric correction technique development
6) Bidirectional modeling
7) Sampling strategy
8) Temporal phenological/response characteristics study. Identification of critical periods — number of looks needed/period. Determine number of days within each critical time period for range evaluation
9) Correction of spectral data for slope — aspect, sensor geometry, and shadow effects
10) Polarization studies
11) Use laser light source to study polarization effects
12) Pre-launch study of data product needs, spatial and spectral preprocessing, and data registration
13) Pre-launch study to select several common test sites for future investigation.

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V. Benefits of Flying With the Thematic Mapper

1) Multistage sampling approach

2) Comparison with broad TM bands

3) Can make atmospheric corrections and apply them to Thematic Mapper data

4) Availability of mid IR and thermal IR data that could be combined with MRS data

5) Improved locational accuracy. This will allow the investigator to more easily locate the MRS data.

VI. Impact of Flying Without the Thematic Mapper

MRS should be launched so that it follows closely behind the Thematic Mapper. If a different orbit configuration is chosen, the time of overpass should be changed to 10:30 - 11:00 a.m. There will be less sunangle effects, more energy for the narrow bands and polarization, and it would be a better time of day to observe plant stress.

The Panel would like to see the MRS fly with the Thematic Mapper and have the overpass time of the Thematic Mapper changed.

VII. Data Products

There should be a difference in the way the visual products and digital data products are processed and handled.

Digital products -- system level corrections for all data.

Radiometrically and geometrically corrected data (radiometric calibrations should be made after the MRS is in orbit). Raw data to allow investigators to apply their own corrections.

Photographic products -- Quick look data products should be provided.

Geometrically corrected products at a common scale.

Registration considerations -- Spectral bands should be registered. Spatially registered data at a single pixel size for all view angles should be an option.

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Non-spatially altered data should be available.

Delivery time -- Quick look imagery should be available within 48 hours. Other data products should be available no longer than one month from the acquisition date.

Scenes/month -- Most investigators would want the capability of collecting data on every overpass.

Quick look data could be used to retrospectively order corrected data.

III. SUMMARY OF PRESENTATIONS GIVEN ON MAY 31

3.0 INTRODUCTION

Summaries of the presentations given on the first day of the workshop are presented in this section. The material presented during this session in the form of viewgraphs and slides are included for reference whenever possible.

EDITORIAL NOTE:

The proceedings included in this report are from reconstructed notes taken at the Fort Collins meeting and are not to be considered as the verbatim remarks of the speakers. References to any section of this report should have the prior approval of the individual speaker involved.

3.1 HISTORY OF MRS
DR. MICHAEL CALABRESE

The MRS, as it is presented here, is a product of several years development. The progression of the system concept from background studies into basic technology and design, including changes and refinements resulting from the review of an outside technical group, is similar to the development stages of the Thematic Mapper (TM) (Figure 3.1.1). The exploration into the idea of a "pushbroom" sensor was begun in 1970 (Figure 3.1.2). The idea of making the pushbroom sensor a pointable imager was added in 1973. In 1975, consideration was given to applying the MLA technology to the MSS on Landsat. The design of the MRS was carried out from 1977 to 1979. A technical working group was formed in 1978 to review the sensor concept and design. The MRS as it is presented here is a result of NASA's response to the recommendations of this working group.

It is worthwhile to consider the MRS in the context of the Landsat sensor evolution (Figure 3.1.3). The TM extends the capability of Landsat by the improvement in resolution, the adjustment in the visible bands and the addition of two bands in the reflective IR and a third in the thermal IR. Likewise, the MRS extends our capabilities by allowing additional improvement in resolution, narrower selectable spectral bands, polarization and off-axis pointing. Yet the MRS represents a very different style of data acquisition compared to Landsat (Figure 3.1.3). Because of its narrow swath width, the MRS is not appropriate for <u>inventories</u> of large regions but is intended for sampling selected areas.

The MRS is the first formal utilization of the MLA technology. The advantages of MLA technology are an improved signal to noise ratio, mechanical stability and higher resolution capability (Figure 3.1.4). Given these advantages, MLA technology may eventually be used to upgrade inventory instruments, such as carried on Landsat. The MRS, however, is a research instrument. (The MRS science objectives are listed in Figure 3.1.5.) The conceptual design of the MRS reflects this research orientation; the MRS is extremely flexible in terms of multiple applications. Although the design of the instrument has undergone a long development, it is still in the planning stages. We need input from the research community in order to make the instrument as useful as possible; however, changes must be considered in the light of the very real constraints (money, technology, etc.).

THEMATIC MAPPER BACKGROUND STUDIES

TITLE	AUTHOR	DATE
• LANDSAT-D THEMATIC MAPPER TECHNICAL WORKING GROUP	JSC/PURDUE	6/75
• THEMATIC MAPPER SPECIFICATION STUDIES	GISS	4/76
• RECOMMENDATIONS FOR THEMATIC MAPPER SPECTRAL BANDS	GSFC	4/76
• INVESTIGATION OF LANDSAT FOLLOW-ON THEMATIC MAPPER SPATIAL, RADIOMETRIC, AND SPECTRAL RESOLUTION	ERIM	6/76
• ANALYSIS OF FIELD SIZE DISTRIBUTIONS	GSFC	6/76
• PRACTICAL APPLICATIONS OF LANDSAT DATA FOR EARTH RESOURCES SURVEY	JSC	9/76
• RESOURCE AND ENVIRONMENTAL SURVEYS FROM SPACE WITH THE THEMATIC MAPPER IN THE 1980'S	NAE/NRC	1976
• TERSSE OPERATIONAL SYSTEMS STUDY	GE	9/75
• SIGMA SQUARED STUDY	GE	11/76
• LANDSAT FOLLOW-ON: A REPORT BY THE APPLICATIONS SURVEY GROUP	JPL	12/76
• A SUMMARY OF THE USER PERSPECTIVE OF LANDSAT-D	NASA HQS.	1/77
• A COST-BENEFIT EVALUATION OF THE LANDSAT FOLLOW-ON OPERATIONAL SYSTEM	GSFC	3/77

Figure 3.1.1. Thematic Mapper Background Studies

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MULTISPECTRAL RESOURCE SAMPLER

• SOLID-STATE PUSH BROOM RESEARCH INITIATED	1970
• HIGH-RESOLUTION POINTABLE IMAGER STUDY	1973
• SOLID-STATE MSS STUDY	1975
• CONCEPTUAL DESIGN	OCT 1977–OCT 1979
• PROJECT TEAM ESTABLISHED	MAR 1978
• SCIENCE WORK GROUP ESTABLISHED	MAR 1978
– MEETINGS	JUN, OCT 1978 FEB, MAY, NOV 1979
• WORKSHOP	MAY 1979
• STAAC COMMITTEE REVIEW	APR 1979

Figure 3.1.2. MRS Development

LANDSAT SENSOR EVOLUTION

IOC	SENSOR	SW	IFOV	VISIBLE/NIR	SWIR	TIR	RATIONALE
1972	MSS	185KM	80M	4 BANDS	-	-	BASE CAPABILITY
1972/78	RBV	185KM	80/40M	1 BAND	-	-	MONOCHROMATIC BACKUP TEST 40M DATA.
1981	TM	185KM	30M	4	2	1	TEST IMPROVED SPECTRAL, RADIOMETRIC, SPATIAL RESOLUTION
MID-1980'S	MRS	15/30KM	15/30M	4/20	-	-	TEST SAMPLING WITH OFF-AXIS POINTING, IMPROVED TEMPORAL RESOLUTION AND NARROW BANDS
LATE-1980'S	MRS MKII	15/30KM	15/30M	4/20	2/4	-	ADD SWIR TO SAMPLER

Figure 3.1.3. Landsat Sensor Evolution

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MULTISPECTRAL RESOURCE SAMPLER

- OFFERS CAPABILITY OF BEING MOST EFFICIENT MEANS OF COMPLIMENTING INVENTORY DATA BY IMPROVING TEMPORAL, SPATIAL, AND SPECTRAL RESOLUTION FOR SELECTED AREAS

- PROVIDES AN EXCELLENT MATCHUP WITH PUSHBROOM TECHNOLOGY
  - ELECTRONIC SCANNING IS INHERENTLY MORE RELIABLE
  - IMPROVED SIGNAL-TO-NOISE (300/1) OVER POINT SCANNERS PERMITS SMALLER, MORE EASILY POINTED MIRRORS AND OPTICS, AND NARROWER BANDS
  - PROVIDES A LOGICAL SCENARIO TO DEVELOP PUSHBROOM TECHNOLOGY IN POINTABLE SENSORS FOR LATER APPLICATION TO INVENTORY SENSORS WHERE PACKAGING, CALIBRATION, AND DATA HANDLING IS MORE DIFFICULT

- POINTABILITY WILL <u>REQUIRE</u> RESEARCH IN:
  - ANISOTROPIC REFLECTANCE - SIDE-TO-SIDE POINTING (BEYOND INVENTORY FRAME) TO OBSERVE SAME SEGMENT FROM DIFFERENT ANGLES
  - ATMOSPHERIC CORRECTION - FORE AND AFT POINTING TO OBSERVE SAME SEGMENT THROUGH DIFFERENT ATMOSPHERIC PATH LENGTHS
  - RADIOMETRIC AND GEOMETRIC CORRECTION
  - REGISTRATION

Figure 3.1.4. Multispectral Resource Sampler

MRS SCIENCE OBJECTIVES

- DEVELOP, TEST AND DEMONSTRATE IMPROVEMENT IN PERFORMANCE, RELATIVE TO MSS AND TM, DUE TO:
    - INCREASED TEMPORAL RESOLUTION
    - SAMPLING MODE (IN CONJUNCTION WITH INVENTORY MODE)
    - CORRECTION OF ATMOSPHERIC EFFECTS
    - INCREASED SPECTRAL RESOLUTION
    - INCREASED SPATIAL RESOLUTION
    - POLARIZATION MEASUREMENTS
- TEST ON-BOARD DATA COMPRESSION TECHNIQUES
- DEMONSTRATE FEASIBILITY OF MULTIPLE IN-FLIGHT SENSOR PARAMETER SELECTION

Figure 3.1.5. MRS Science Objectives

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3.2 THE MRS SENSOR
DR. CHARLES SCHNETZLER
(SEE APPENDIX A FOR A MORE COMPLETE DISCUSSION OF THE MRS)

In this morning's session of the workshop, we want to bring you up to date on the MRS design, its capabilities and limitations. It should be kept in mind that the goals of the MRS (Figure 3.2.1) are research goals: It is a research tool not an operational device. The capabilities of the MRS are unique but research is needed on the possible applications before such a system can become operational. This instrument will provide NASA with its first engineering test of MLA technology.

The MRS is a pushbroom scan sensor. Pushbroom scanning is a term which describes the technique of using the forward motion of a satellite platform to sweep a linear array of detectors oriented perpendicular to the ground track across a scene being imaged (Figure 3.2.2). Satellite motion provides one direction of scan and electronic sampling of the detectors in the crosstrack dimension provides the orthogonal scan component to form an image. The detector array is sampled at the appropriate rate to produce continuous lines.

This pushbroom scan, which is feasible because of the MLA technology, makes possible improvements in performance which are not really possible with the mechanical scan technology. The MRS, as a research instrument, utilizes these improvements in performance (Figure 3.2.3). These include improvements in spatial, spectral and temporal resolution along with a polarization capability not yet available on a satellite system. Other science objectives of the MRS are to test on-board data compression techniques and to demonstrate the feasibility of multiple in-flight sensor parameter selection (e.g., filters, pointing direction). The MRS has a rather narrow swath width; thus, the MRS is a sampling instrument rather than an inventorying instrument. Another science objective of the MRS will be to explore the use of the sampling mode in conjunction with the inventory mode.

The system which we are describing today has been under consideration for some time (Figure 3.2.4). The present design is a result of interactions of GSFC with the MRS Science Working Group (Figure 3.2.5). Figure 3.2.6 shows the sensor characteristics. Several of these characteristics are limited in some way by the constraint of designing the MRS to fit in the MSS slot conform-

GOALS OF THE MRS

- TO PROVIDE UNIQUE RESEARCH CAPABILITIES FOR EARTH SURVEY APPLICATIONS EXPERIMENTS BEYOND THOSE POSSIBLE WITH THE THEMATIC MAPPER

- TO PROVIDE NASA's FIRST ENGINEERING TEST OF MULTISPECTRAL LINEAR ARRAY TECHNOLOGY

- TO VALIDATE NEW, OPERATIONAL, EARTH OBSERVATIONAL MISSIONS BY THE IMPROVED PERFORMANCE OF THE MRS

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CCS/GSFC

Figure 3.2.1. Goals of the MRS

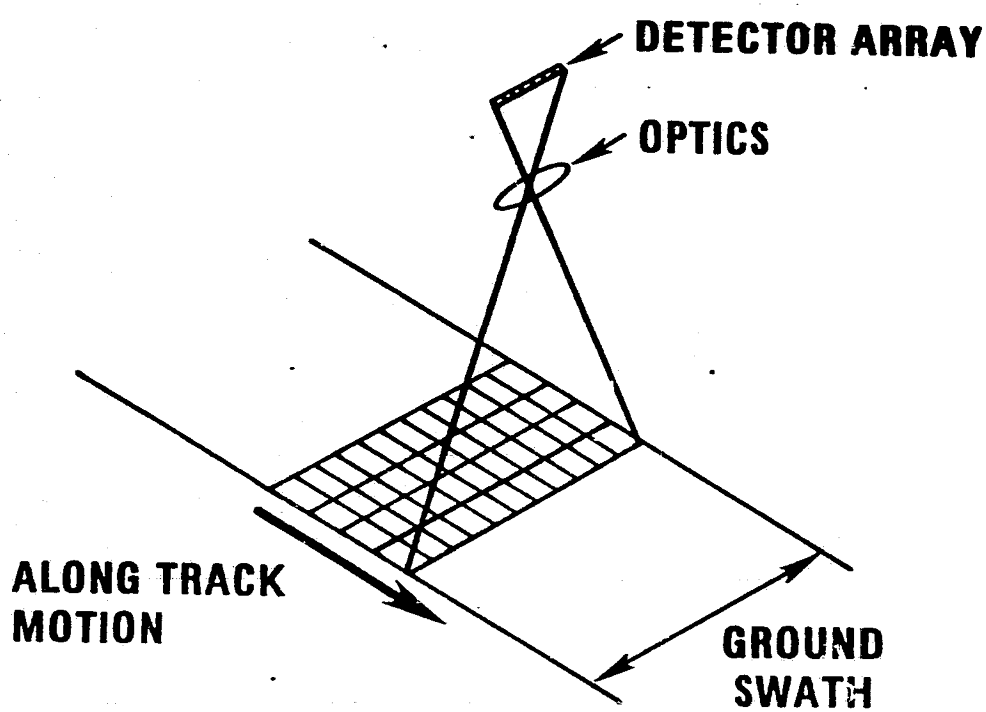

Figure 3.2.2 Pushbroom Scanning Technique Type In Multispectral Linear Array

CONCEPT:

Subtend the image of the across track swath using a line array of detectors...use the along track orbital motion to provide one dimension of scan and electronically sample the detectors in across track dimension thus forming the required raster.

MRS SCIENCE OBJECTIVES

DEVELOP, TEST AND DEMONSTRATE IMPROVEMENT IN PERFORMANCE, RELATIVE TO MSS AND TM, DUE TO

- INCREASED TEMPORAL RESOLUTION
- SAMPLING MODE (IN CONJUNCTION WITH INVENTORY MODE)
- CORRECTION OF ATMOSPHERIC EFFECTS
- INCREASED SPECTRAL RESOLUTION
- INCREASED SPATIAL RESOLUTION
- POLARIZATION MEASUREMENTS

TEST ON-BOARD DATA COMPRESSION TECHNIQUES

DEMONSTRATE FEASIBILITY OF MULTIPLE IN-FLIGHT SENSOR PARAMETER SELECTION.

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Figure 3.2.3. MRS Science Objectives

MRS HISTORY

'69-'72	MLA FEASIBILTY STUDY
'72-'76	BREADBOARD LINEAR ARRAY PROGRAM
'73-'75	HRPI SENSOR STUDY
'77	ELECTRONICS, CCD CHIP EVALUATION
FEB. '78	REQUEST BY HDQTS TO CONSIDER MLA SENSOR OPTIONS
MARCH '78	FIVE OPTIONS PRESENTED TO TUWG AND AD HOC GROUP
	RECOMMENDATION OF POINTING, MIXED RESOLUTION (30/15 M), SELECTABLE FILTERS
APRIL-MAY '78	RISK ASSESSMENT OF MIR & TIR BANDS
JUNE '78 NOV. '78 FEB. '79	MEETINGS OF MRS SCIENCE WORKING GROUP
MAY '79	MRS WORKSHOP

Figure 3.2.4. MRS History

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MRS SCIENCE WORKING GROUP MEMBERS

DR. JOHN ESTES	U. OF CALIFORNIA, SANTA BARBARA
DR. DAVID GOLD	PENN STATE UNIVERSITY
DR. EDWARD KANEMASU	KANSAS STATE UNIVERSITY
DR. VYTAUTAS KLEMAS	UNIVERSITY OF DELAWARE
DR. EUGENE MAXWELL	COLORADO STATE UNIVERSITY
DR. LEE MILLER	TEXAS A&M UNIVERSITY
DR. GARY PETERSON	PENN STATE UNIVERSITY
DR. ROBERT REGAN	UNIVERSITY OF MARYLAND
DR. PHILIP SLATER	UNIVERSITY OF ARIZONA
DR. JIM SMITH	COLORADO STATE UNIVERSITY
DR. ROBERT TURNER	SCIENCE APPLICATIONS, INC.

Figure 3.2.5. MRS Science Working Group Members

MRS Sensor Characteristics

Spectral Range:	0.36 μm to 1.0 μm
Spectral Bands:	4 arrays, each with 2000 detectors 5 selectable filters/array Bandwidths $\geq$ 20 nm Polarization filters
Spatial Resolution:	15 meters max
Swath Width/Modes:	15 km at 15 m (4 bands) 30 km { at 15 m (2 bands) at 15 m (4 bands, 50% sampling) at 30 m (4 bands)
Radiometric Sensitivity:	Approximately 0.5% NE$\Delta\rho$ (8 bit)
Data Rate:	15 mega bits/sec.
Pointability:	2 axes + 40° across track + 55° along track
Speed of Pointing:	30°/sec across track 5°/sec along track

Figure 3.2.6. MRS Sensor Characteristics

ing to the MSS size, weight and data rate. One of these constraints may be removed: the 15 megabit/second data rate may be increased to 30 megabits/second. One of the topics you will be asked to consider is how the higher data rate can be best used if it becomes available.

The improved temporal resolution available with the MRS is a direct result of the pointing capability. Figure 3.2.7 shows the pattern of coverage assuming that the MRS is in the Landsat orbit with a 16-day return-time. The frequency of return coverage is shown for 3 different latitudes.

Figure 3.2.8 shows the current list of filters planned for the MRS. This list was developed in conjunction with the MRS Science Working Group. Each of the four arrays will have a filter wheel (vertical column), and each filter wheel will contain five filters. Each wheel is indexed independently. Thus, an experimenter can choose (in-flight) a filter from each column.

The MRS will also have four selectable operating modes as shown in Figure 3.2.9. These four modes all conform to the 15 megabit/sec. data rate limit. Fail-safe mechanisms are also planned such that, should anything go wrong with the filter selection, the default selection would be the TM bands; if anything goes wrong with the pointing, the MRS would default to a nadir view. The selectable variables are listed in Figure 3.2.10.

Figure 3.2.11 compares some of the physical characteristics of the MRS and the TM.

The experimental program for the MRS (Figure 3.2.12) should include experiments from all disciplines. Some of these experiments would be directly funded by NASA while others might be funded by outside sources. Other "unofficial" experiments would be accepted as scheduling permits. During any unscheduled time MRS could be obtaining nadir, 15 m resolution data to be archived with TM data.

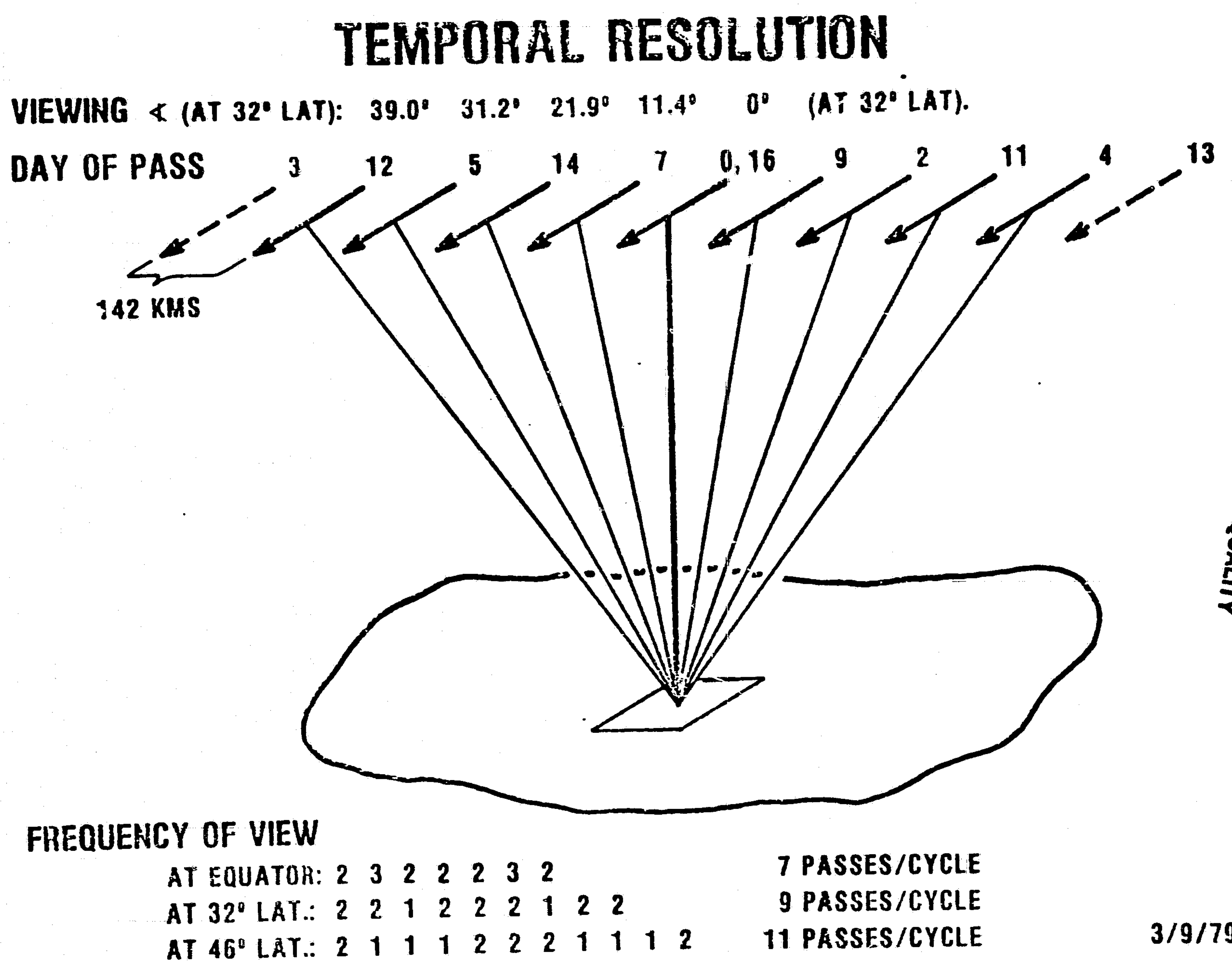

Figure 3.2.7. Illustration of the Improved Temporal Resolution Provided by the MRS

MRS SPECTRAL BANDS

		ARRAY NO.				REMARKS
		1	2	3	4	
FILTER POSITION	1	450-520 TM 1	520-600 TM 2	630-690 TM 3	760-900 TM 4	THEMATIC MAPPER BANDS
	2	540-560	670-690	710-730	780-800	VEGETATION
	3	840-860	880-900	730-750	400-420	GEOL. VEG
	4	360-400	TM 3 VERT.	930-950	490-510	ATMOS. LAND USE POLAR.
	5	TM 4 VERT.	TM 4 HORZ.	TM 2 HORZ.	TM 3 HORZ.	POLARIZE

UNITS IN NANOMETERS

Figure 3.2.8. MRS Spectral Bands

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MRS SENSOR OPERATING MODES

MODE	RESOLUTION (IFOV)	SWATH WIDTH	NO OF BANDS	DETECTORS/ BAND	NOTES
1	15 m	15 km	4	1000	SELECTABLE FROM 2000
2	15 m	30 km	2	2000	
3	30 m	30 km	4	2000	ON-BOARD AVERAGING OF EACH OF TWO DETECTORS
4	15 m	30 km	4	1000	EVERY OTHER DETECTOR

11/13/78
KID

Figure 3.2.9. MRS Sensor Operating Modes

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MRS VARIABLES TO BE SELECTED IN FLIGHT

LOCATION OF VIEW

INPUT LAT./LONG. OF SITE - DIRECTS POINTING ($\pm 55^\circ$ ALONG TRACK, $\pm 40^\circ$ ACROSS TRACK)

SWATH WIDTH/# OF BANDS/RESOLUTION

FOUR MODES

SPECTRAL FILTERS

FIVE FILTERS/ARRAY, INCLUDING POLARIZATION FILTERS

QUANTIZATION LEVELS

8 TO 10 BITS

5/15/79
CCS/GSFC

Figure 3.2.10. MRS Variables to be Selected In-flight

COMPARISON OF MRS AND TM CHARACTERISTICS

	MULTISPECTRAL RESOURCE SAMPLER	THEMATIC MAPPER
OPTICS APERTURE	20 CM	42 CM
FOCAL LENGTH	70 CM	320 CM
WT	55 KG	220 KG
SIZE	1.6 M x 0.5 x 0.6 M	2.0 M x 1.1 M x 0.6 M
# DETECTORS/BAND	2000	16
POWER	55 W	250 W

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Figure 3.2.11. Comparison of MRS and TM Characteristics

POTENTIAL EXPERIMENT PROGRAM

- LIMITED NUMBER OF EXPERIMENTS CHOSEN THROUGH NASA ANNOUNCEMENT OF OPPORTUNITY
- EXPERIMENTS SOLICITED IN ALL DISCIPLINES--AG, FORESTRY, RANGELAND, LAND USE, GEOLOGY, WATER RESOURCES, OCEANOGRAPHY, ATMOSPHERICS
- APPROXIMATELY 30 EXPERIMENTS
  - FUNDED (E.G., UNIVERSITY AND INDUSTRY)
  - NON-FUNDED FOREIGN
  - NON-FUNDED U.S. (E.G., OTHER FEDERAL AGENCIES)
- EXPERIMENTS TO RUN APPROXIMATELY 4 YEARS--2 PRE- AND 2 POST-LAUNCH
- OTHER, "UNOFFICIAL," EXPERIMENTS ACCEPTED AS SATELLITE TIME AND DATA HANDLING FACILITIES PERMIT
- WHEN NOT PERFORMING EXPERIMENTS, THE MRS COULD BE TAKING 15 M NADIR DATA TO BE ARCHIVED WITH TM DATA

Figure 3.2.12. Potential Experiment Program

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3.3 MLA TECHNOLOGY
MR. LESLIE THOMPSON
(SEE APPENDIX B FOR ADDITIONAL INFORMATION)

MLA technology will allow a significant improvement in sensor performance for remote sensing. This new generation of sensor operates on a principle different from the electromechanical scanners. The differences will be described here in some detail. To set the stage for this discussion consider the orbital situation (Figure 3.3.1). This situation is the same for all imaging techniques. In all cases an area on the earth, within the field of view of the sensor, is imaged at the satellite.

There are basically three ways to obtain the image. These are illustrated in Figure 3.3.2.

- Framing mode - imaging all the points simultaneously. This is the technique used for the Landsat Return Beam Vidicon (RBV).
- Point detector - imaging one point at a time. This requires mechanical motion in the optics. There are three variations on this technique: the linear, unidirectional scan used on the Landsat MSS, the linear, bidirectional scan which will be used on the TM, and the conical scan used on the Skylab scanner.
- Pushbroom scan mode - imaging all of the points on one line simultaneously. This, of course, is the mode which will be used on the MRS.

We will first consider the mechanical scan technique, illustrated in Figure 3.3.3. The scan is accomplished by moving a scanning mirror to sequentially image areas in the cross track direction. A single detector views a particular resolution element for about 15 μs for the MSS and about 10 μs for the TM. This short dwell time limits the sensitivity of the instrument.

The analog signal from the detector is amplified and prepared for digital conversion. On the TM this is accomplished by the complex amplifier chain illustrated in Figure 3.3.4. There are 96 individual signal amplifiers like this on the TM - one for each of the 16 detectors used in each band. The TM is a product of an evolutionary growth in the mechanical scan technology. Compared to the MSS it will provide improved spatial resolution (30 m IFOV), additional and narrower spectral bands (seven), and increased instrument sensitivity (256 gray

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THE ORBITAL SITUATION

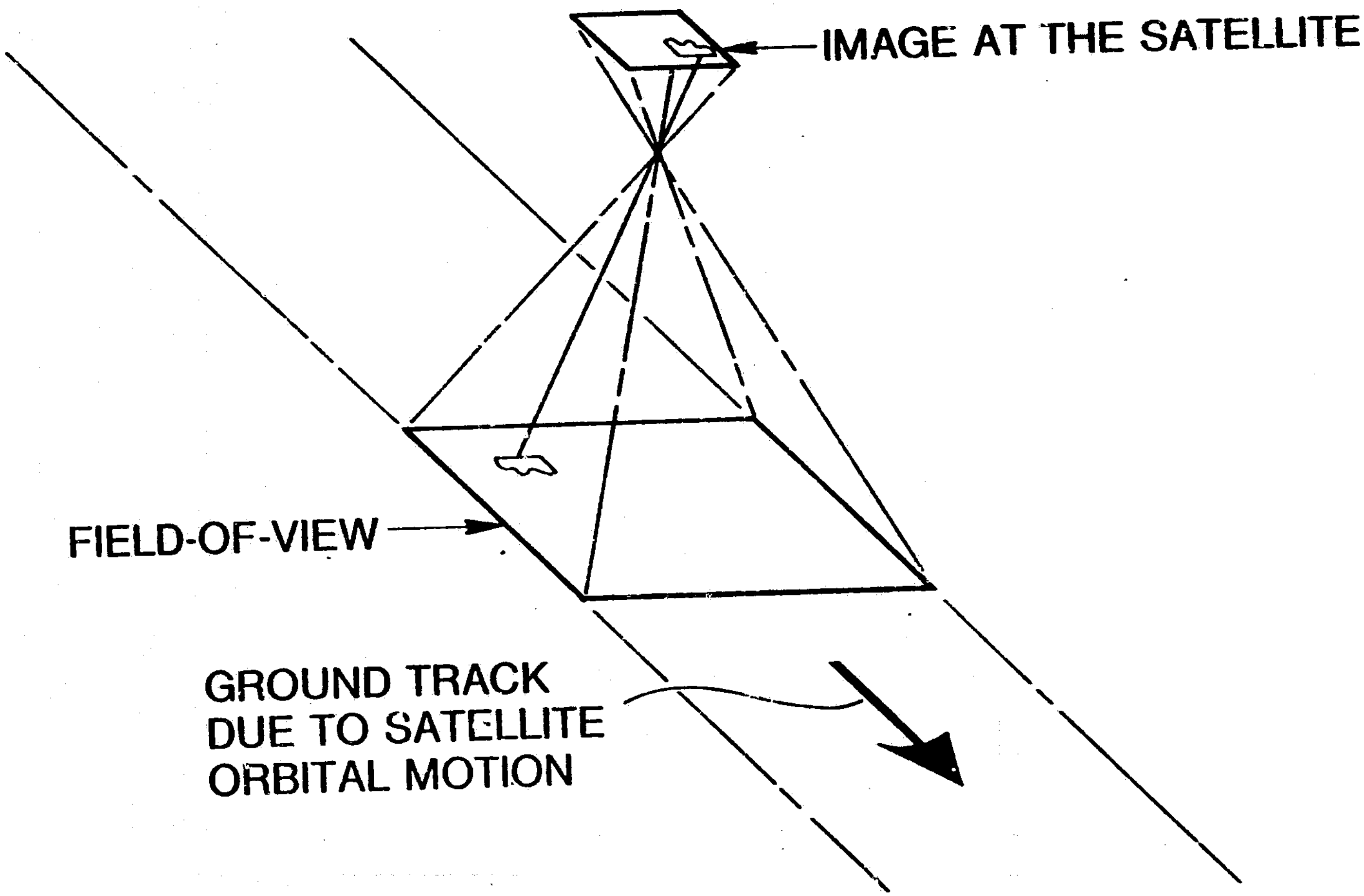

Figure 3.3.1 The Orbital Situation

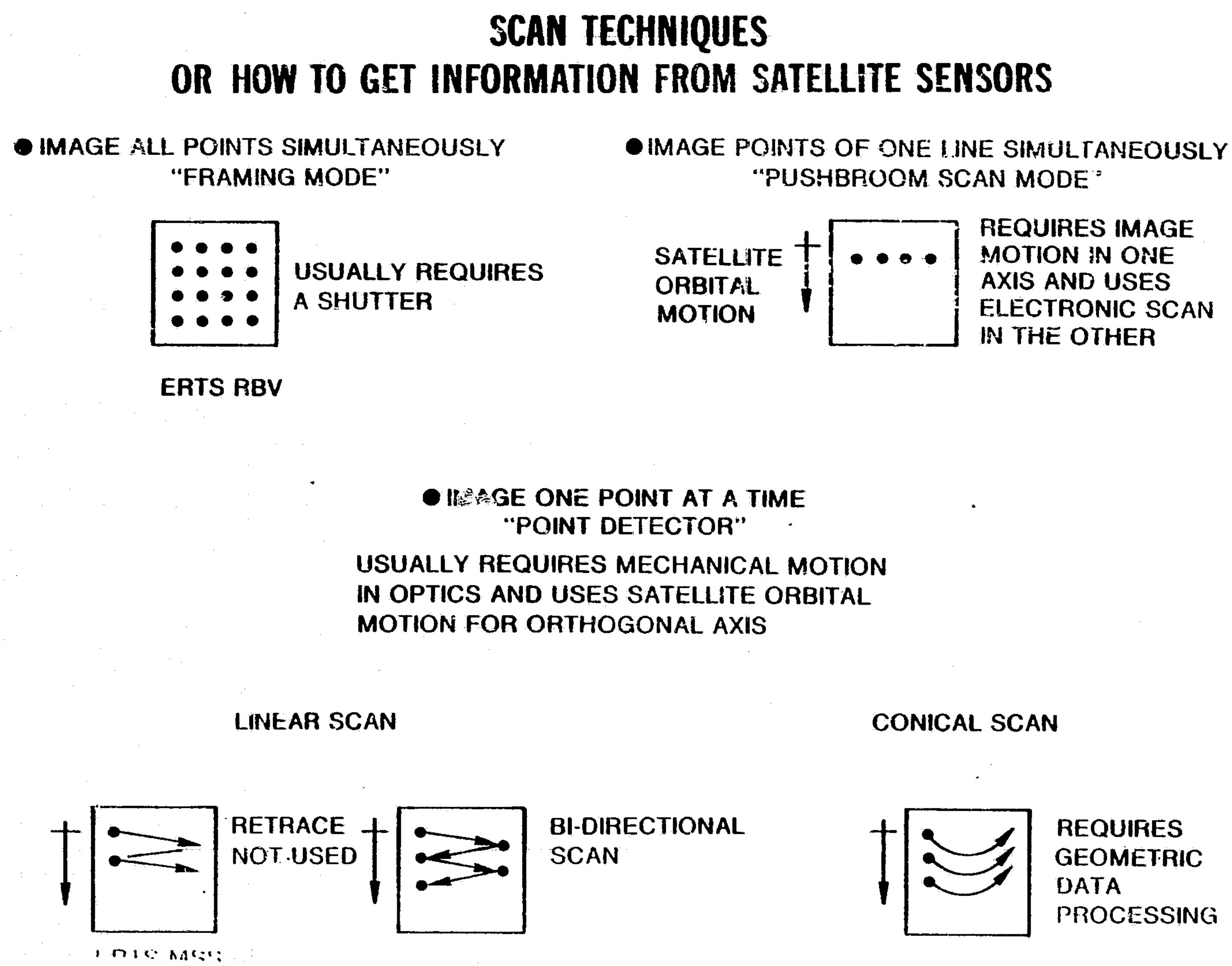

Figure 3.3.2 Scan Techniques

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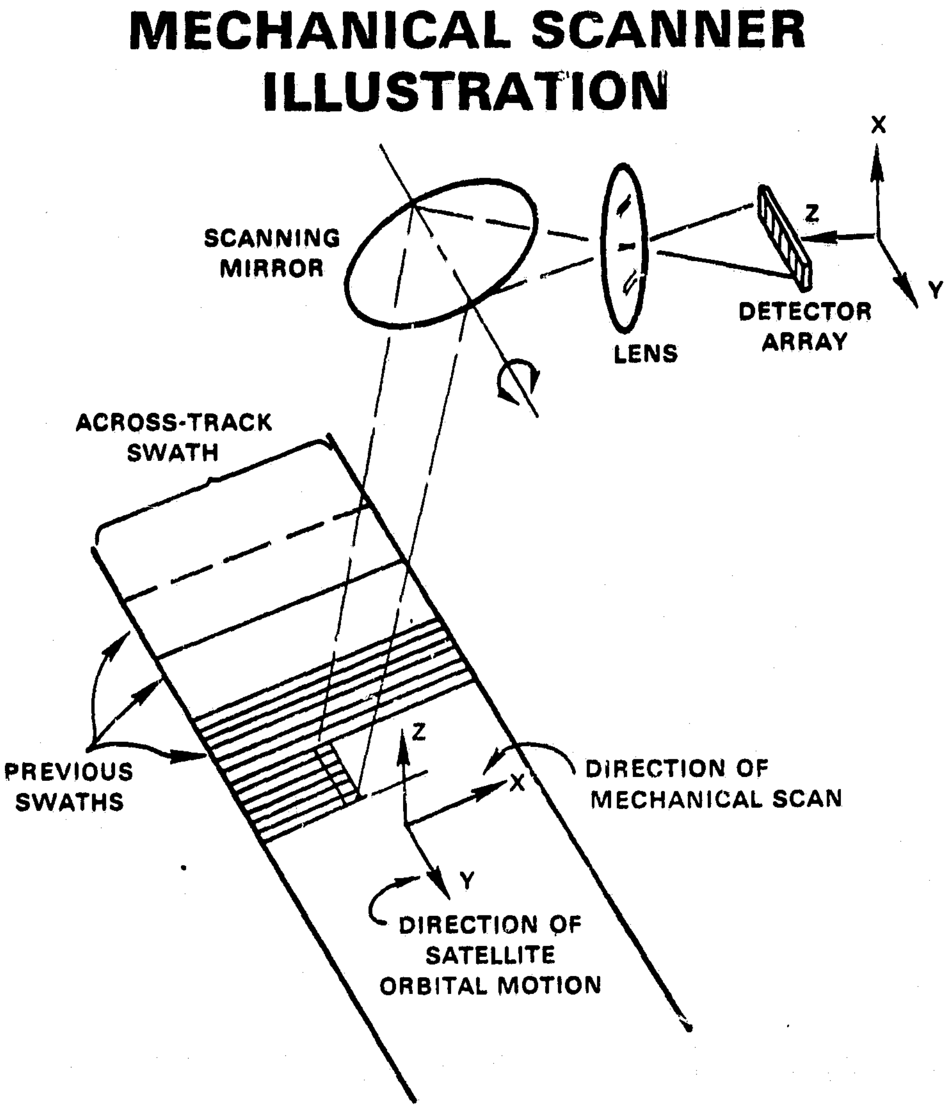

Figure 3.3.3 Mechanical Scanner Illustration

ANALOG/DISCRETE VIDEO CHAIN FOR THE THEMATIC MAPPER

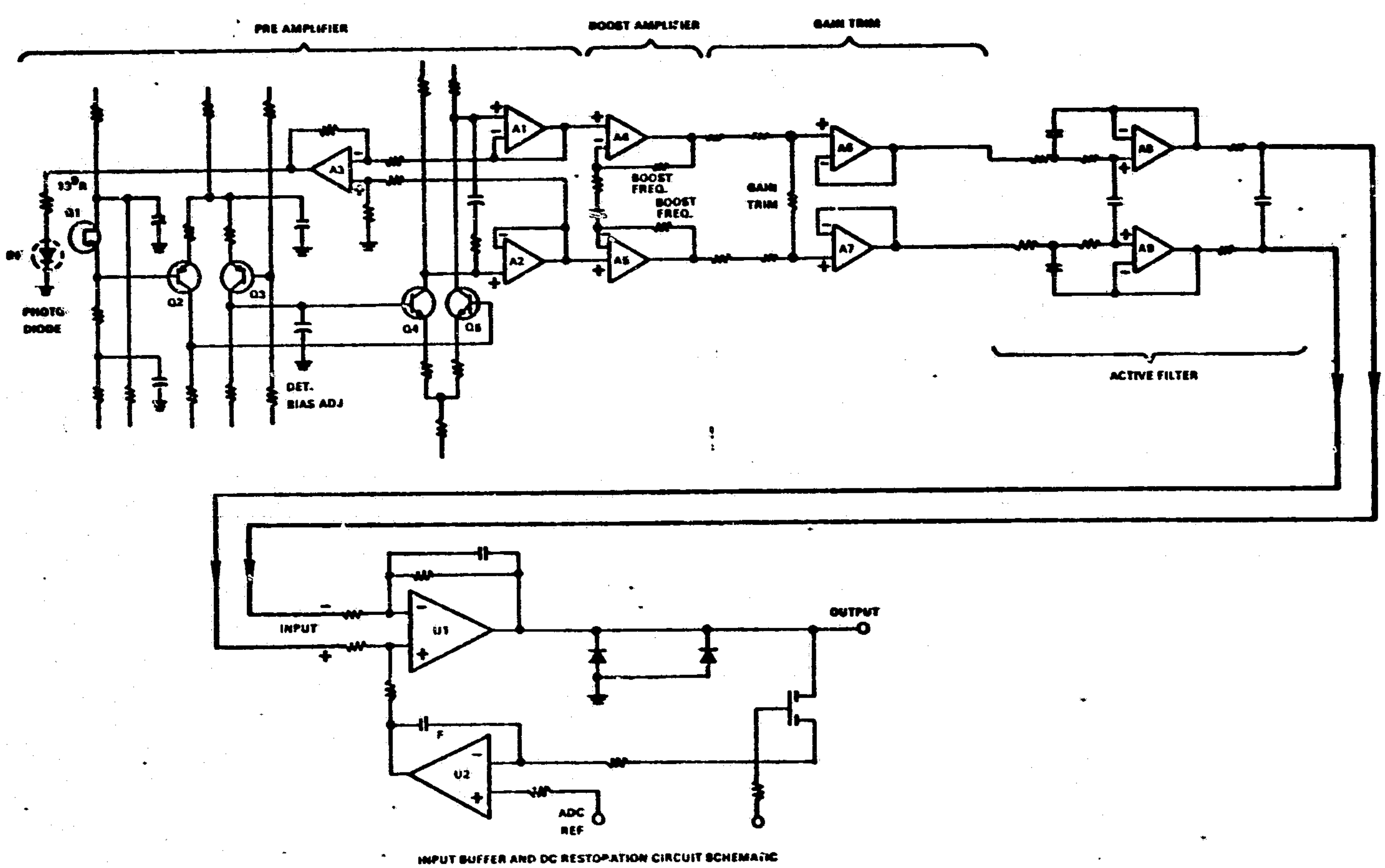

Figure 3.3.4 Analog/Discrete Video Chain For The Thematic Mapper

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levels), yet these improvements represent a limitation. Figure 3.3.5 shows the merit function for electro-mechanical scanners. Electro-mechanical scanners have reached a plateau in development. Any further improvements in performance will be increasingly costly for only small increments in performance ability.

Multispectral sensors using the MLA technology are not so limited. As Figure 3.3.5 shows, a scanner equivalent to the MSS using MLA technology has a far higher merit function than the MSS. Furthermore, there is potential for significant improvement in performance in the forseeable future when using solid state linear arrays and operating in a "pushbroom" mode.

In the pushbroom mode, illustrated in Figure 3.3.6, a linear array of detectors image an across track swath. The satellite motion provides one dimension of scan and electronic sampling of the detectors provides the other. This scan method has several advantages and disadvantages. These are listed in Figure 3.3.7. The most obvious advantage is the elimination of any complex mechanical scan mechanisms. Perhaps even more important is the improved radiometric sensitivity; each detector covers only one resolution element in the along track direction which allows for a much longer integration time (2 to 10 ms) than would be possible with the MSS or TM. The improvement in the signal to noise ratio is quite significant and permits smaller aperture optics to be used with a consequent reduction in size and weight of the instrument.

Another advantage of the MLA's is that the detector positions can be precisely known, allowing better geometric accuracy. Finally, offset pointing becomes relatively easy.

There are also some difficulties with the MLA technology. The major problem is that there are now a large number of detectors all requiring separate calibration.

How can these long arrays which have thousands of elements be manufactured? If discrete amplifier components were required for each detector as in the MSS, the problem would be enormous. However, solid state integrated circuit technology provides the answer. Hundreds to over a thousand detectors can be manufactured on a single monolithic chip of silicon along with low noise amplifiers and multiplexing circuits.

HISTORICAL TREND IN EARTH-VIEWING ELECTRO-MECHANICAL SCANNERS MERIT FUNCTION COMPARISON VERSUS LAUNCH DATE

(FOR VISIBLE/NEAR-IR SPECTRAL BANDS)

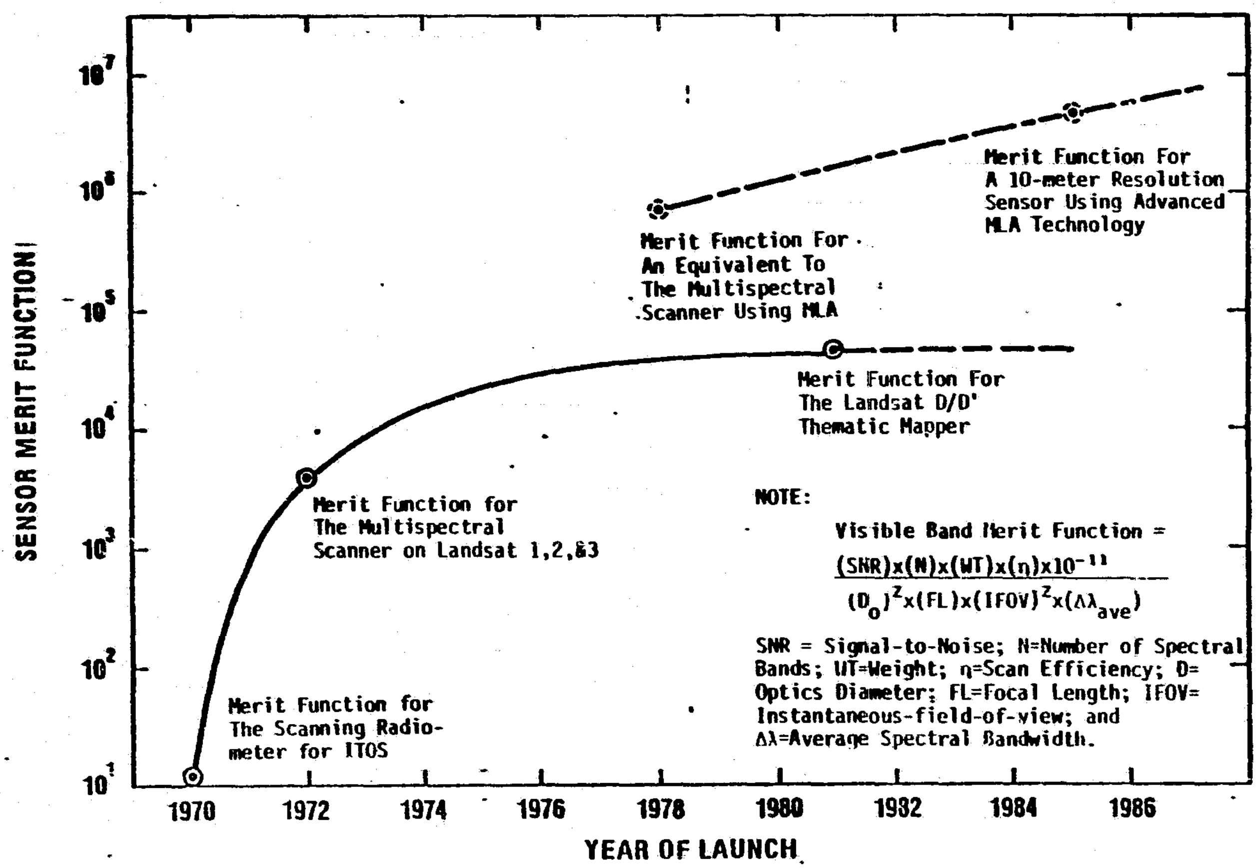

Figure 3.3.5.

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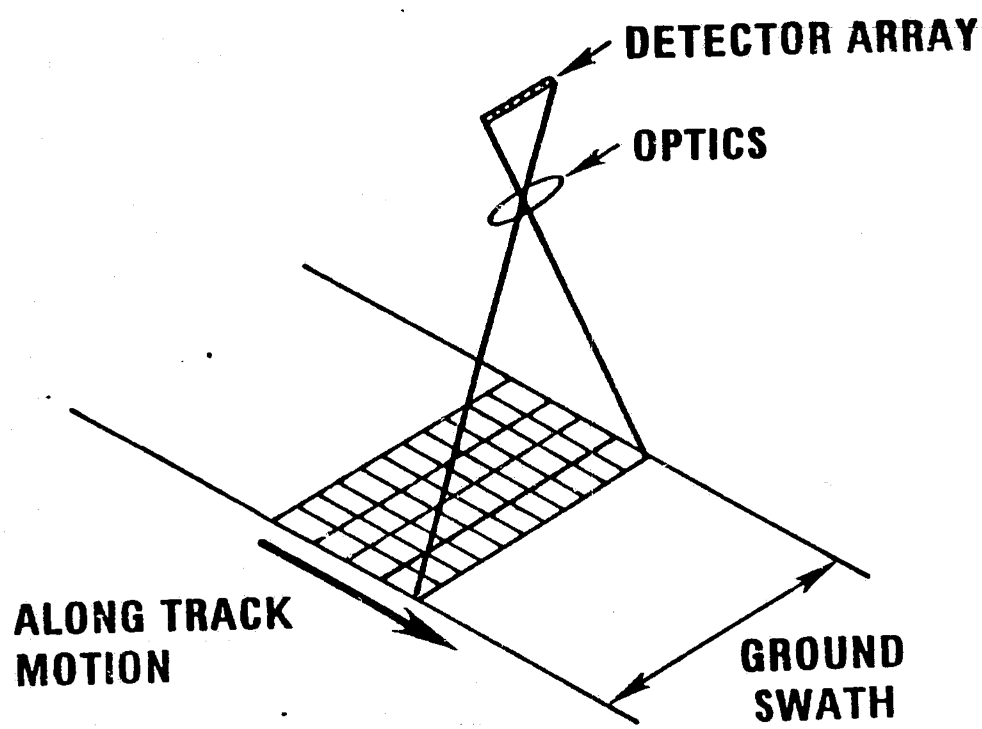

Figure 3.3.6 Multispectral Linear Arrays

CONCEPT:

Subtend the image of the across track swath using a line array of detectors...use the along track orbital motion to provide one dimension of scan and electronically sample the detectors in across track dimension thus forming the required raster.

ADVANTAGES & DISADVANTAGES OF MLA SENSOR SYSTEMS

ADVANTAGES

- IMPROVED RADIOMETRIC SENSITIVITY
  - -- LONG INTEGRATION TIME
- HIGH SCAN EFFICIENCY
- COMPLEX MECHANICAL SCAN MECHANISMS NOT REQUIRED
- DETECTOR POSITIONS CAN BE PRECISELY MAPPED
  - -- CARTOGRAPHIC CONSIDERATION
- OFFSET POINTING CAPABILITY EASY
- CAN PROVIDE SMALLER, LIGHTER WEIGHT LOWER COST OPERATIONAL INSTRUMENT

DISADVANTAGES

- LARGE NUMBER OF DETECTORS REQUIRED
- MORE COMPLEX CALIBRATION
- MORE COMPLEX GROUND DATA PROCESSING

Figure 3.3.7. Advantages & Disadvantages of MLA Sensor Systems

Linear array devices have been under consideration by NASA since 1972 (Figure 3.3.8). In 1976 Westinghouse developed a detector array technology which demonstrated performance adequate for a 10-meter resolution multispectral imaging radiometer. An array assembled under the Westinghouse program used 18 silicon chips (each with 96 detectors) providing a total of 1728 detectors. Detector position within a chip can be precision controlled to 0.05 of a resolution element size with a cumulative error over the length of the array 0.5 of a resolution element. Figure 3.3.9 shows four examples of radiometrically corrected imagery from 576-element detector array. The detector-to-detector variations have been removed by computer processing using a calibration table that was measured and recorded for each detector.

One of the design criteria for the MRS was that it have 0.5% sensitivity in all four spectral bands for a variety of scene conditions; 0.5% sensitivity is defined as the change in target reflectance ($\Delta\rho = 0.005$) equal to the RMS noise of the sensor system. This is the noise equivalent reflectance, $NE\Delta\rho$. Figure 3.3.10 shows the predicted performance of the MRS for the green band ($.45\mu$ - $.52\mu$) for a wide range of solar zenith angles (SZA). For each set of test conditions the predicted $NE\Delta\rho$ is easily below the required 0.5% level. Predicted values for the TM are provided for comparison.

The low noise and high sensitivity characteristics are possible because of the availability of silicon solid state arrays. The silicon arrays to be used for the MRS are sensitive from .36 to 1.0 μ. At present there are no detectors adequate for the thermal infrared region. One major objective for the future is to develop a pushbroom scan array for the 10-12 μ spectral region. The major difficulty with thermal detectors is the need to cool the detectors. The photoconductive HgCdTe detectors must be cooled to 100° K and the power requirements for this cooling are excessive for existing designs. In order to minimize power loss due to cooling it will be necessary to minimize the number of leads into and out of the cold focal plane. Figure 3.3.11 shows the general approach using HgCdTe detectors.

An aircraft, thermal IR, pushbroom scanner is being built as shown in Figure 3.3.12. This system uses a 90-element HgCdTe array and is sensitive in the 10-12 μ range. The simplicity of design of this system assures a high reli-

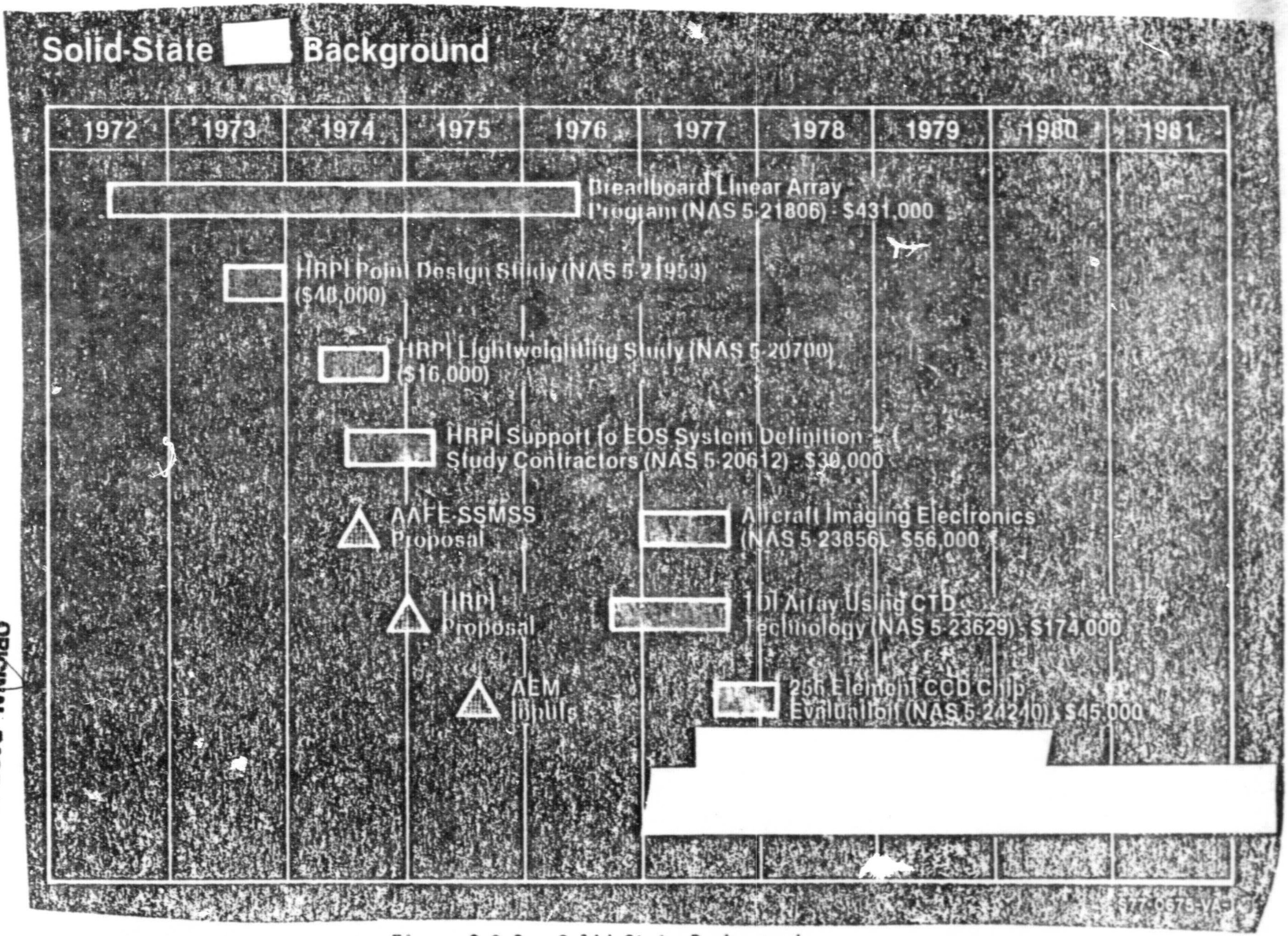

Figure 3.3.8. Solid-State Background

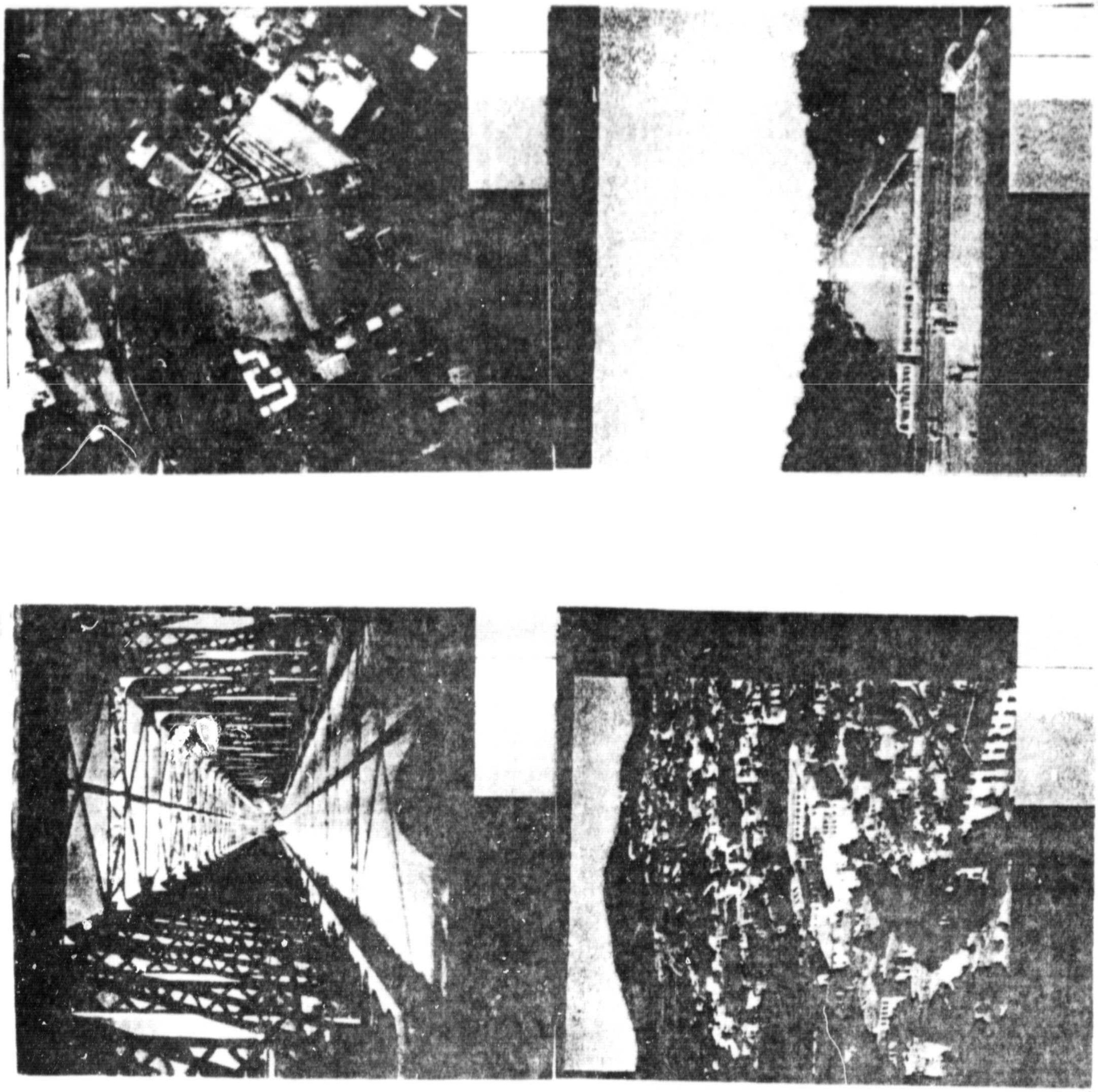

Figure 3.3.9 RADIOMETRICALLY CORRECTED IMAGERY USING A 576 ELEMENT DETECTOR ARRAY

PREDICTED PERFORMANCE
MULTISPECTRAL RESOURCES SAMPLER (MRS)

SPECTRAL BAND — .48um to .52um
PERFORMANCE OVER KANSAS AT VARIOUS TIMES OF YEAR

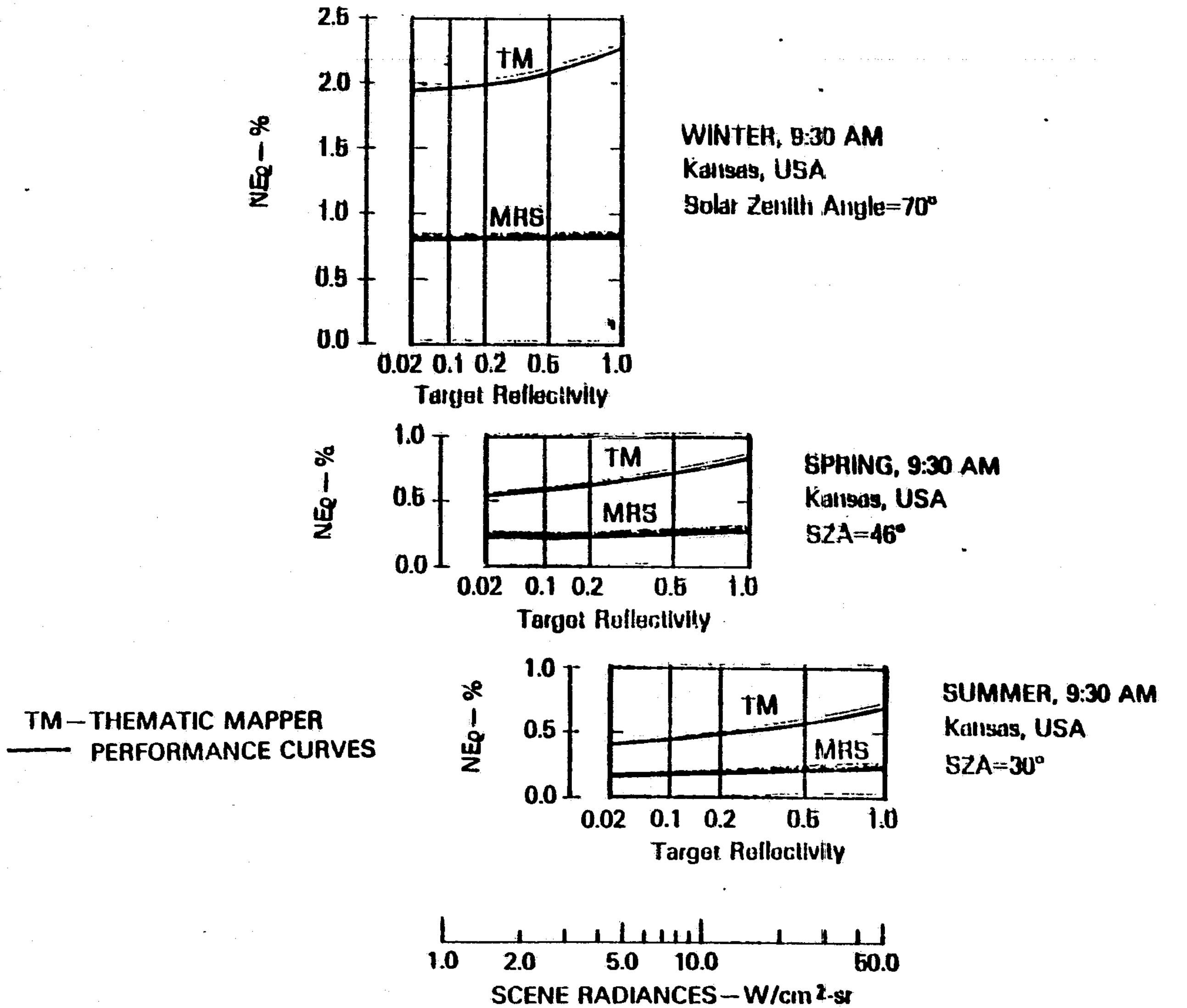

Figure 3.3.10. Predicted Performance Multispectral Resources Sampler (MRS)

HYBRID INFRARED/CCD LINEAR ARRAYS FOR 10-12 μM REGION

OBJECTIVE:

TO DEVELOP A PUSHBROOM SCAN ARRAY TECHNOLOGY FOR THE 10 TO 12 μM SPECTRAL REGION . . . COMPLEMENT CAPABILITY IN SHORT WAVE SPECTRAL BANDS

APPROACH:

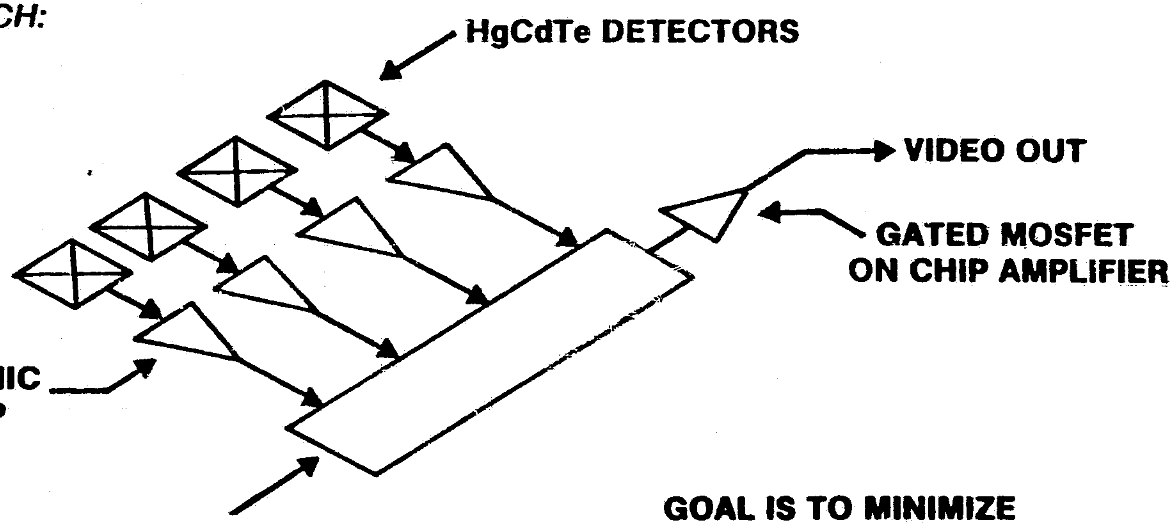

Figure 3.3.11

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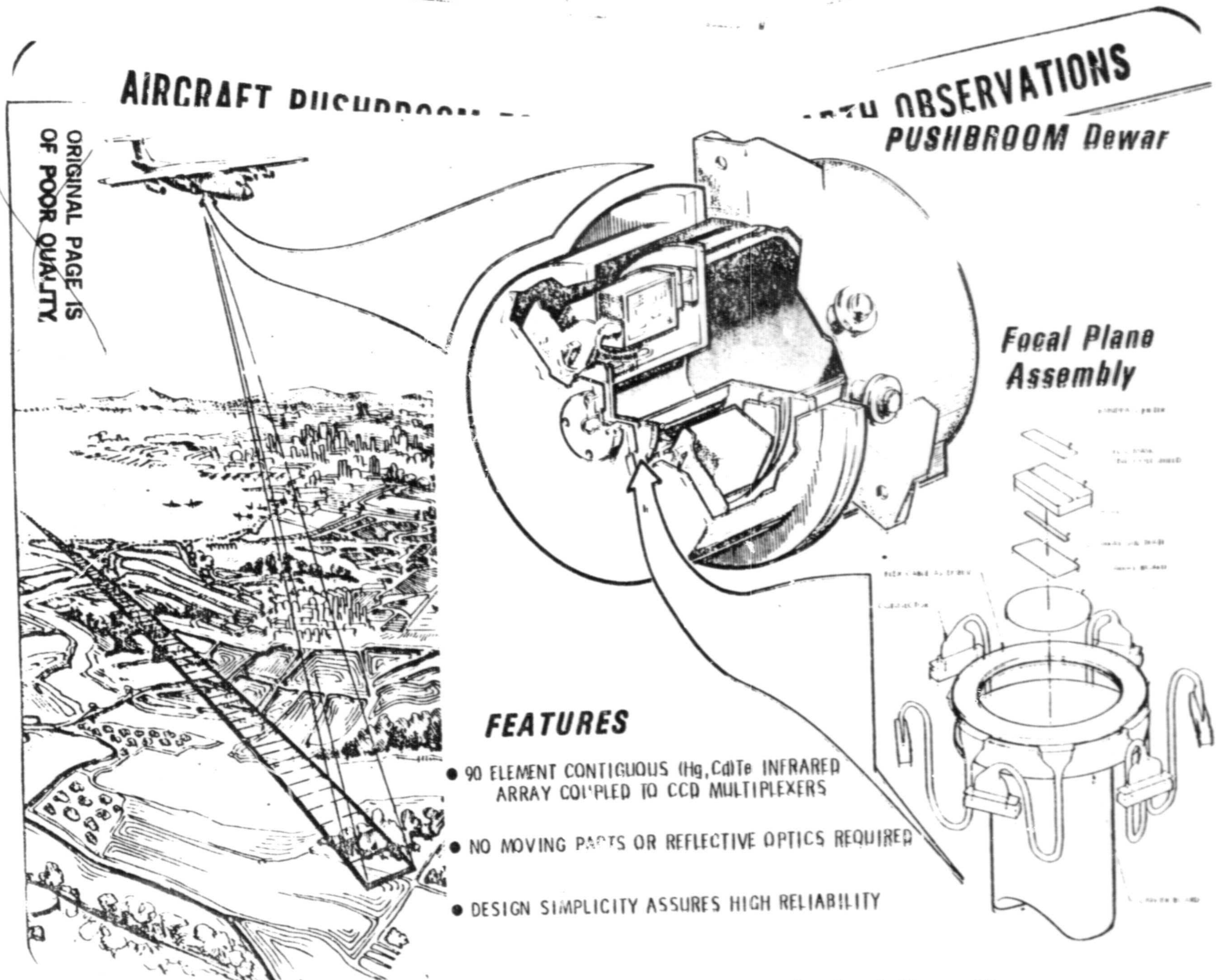

Figure 3.3.12. Aircraft Pushbroom Focal Plane for Earth Observations

ability. The calibration of the system is more difficult, of course, and an aircraft is not as stable a platform as a spacecraft, but the utility of the pushbroom design for thermal IR remote sensing can be demonstrated from aircraft tests.

There are other solid state detectors which could be used to extend the spectral range of pushbroom devices. The temperature of operation and wavelength band of useful response for several of these detectors is shown in Figure 3.3.13.

Figure 3.3.14 shows the technology developments required for arrays for the different spectral regions. For the visible region, intrinsic silicon is the obvious choice both because of its room temperature operation and because of the maturity of the silicon technology. Outside of the visible region there are several candidate detectors. In the short wavelength IR lead sulfide (PbS) is the detector most likely to be developed in the near term largely because of its relatively high operating temperature (200° K). For the long wave (thermal) IR, initial development of the HgCdTe detectors is already underway. Lead-tin-telluride is the only other detector which has a reasonable operating temperature.

C-2

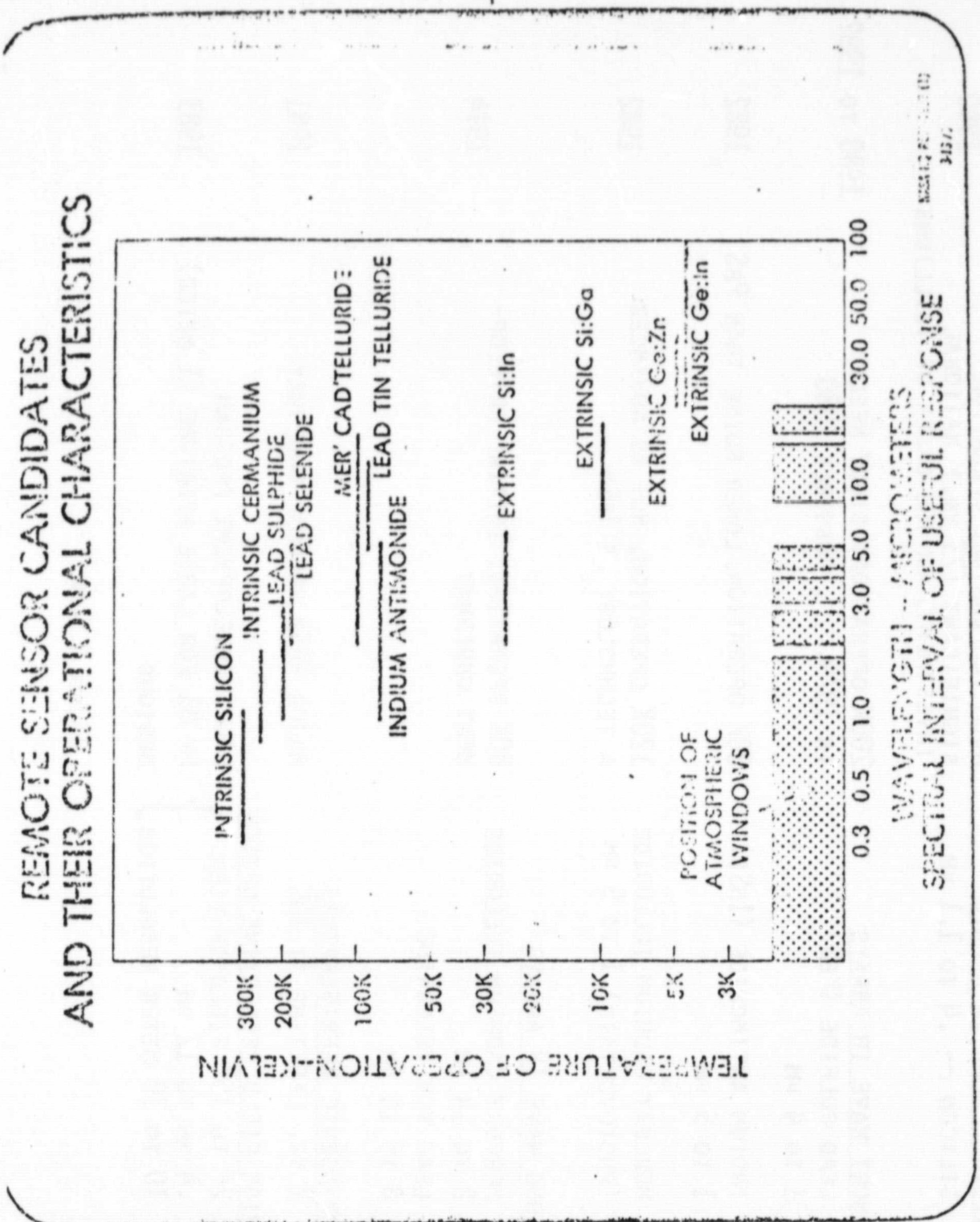
REMOTE SENSOR CANDIDATES
AND THEIR OPERATIONAL CHARACTERISTICS
TEMPERATURE OF OPERATION-KELVIN
300K
200K
100K
50K
30K
20K
10K
5K
3K
INTRINSIC SILICON
INTRINSIC GERMANIUM
LEAD SULPHIDE
LEAD SELENIDE
INDIUM ANTIMONIDE
LEAD TIN TELLURIDE
EXTRINSIC Si:In
EXTRINSIC Si:Ga
EXTRINSIC Ge:In
POSITION OF
ATMOSPHERIC
WINDOWS
0.3
0.5
1.0
3.0
5.0
10.0
30.0
50.0
100
SPECTRAL INTERVAL OF USEFUL RESPONSE

Figure 3.3.13.

TECHNOLOGY DEVELOPMENTS REQUIRED

ACTIVITY	COMMENTS	POTENTIAL START PHASE C/D
VISIBLE/NEAR IR ARRAYS SILICON -- .4 TO 1.1 μM	ROOM TEMPERATURE OPERATION; SIGNIFICANT (25 YR.) NATIONAL INVESTMENT, ON THE ORDER OF $BILLIONS	1980
SHORT WAVE IR ARRAYS LEAD SULFIDE (PbS) 1 TO 4 μM	200K OPERATION; STUDY NEEDED IN 1979. . . POSSIBLE 1980	1980 TO 1982
INDIUM ANTIMONIDE (InSb) 1 TO 5 μM	80K OPERATION; LOWER NOISE THAN PbS	1982
MERCURY CADMIUM TELLURIDE (PHOTOVOLTAIC) 1 TO 5 μM	120K OPERATION; NOT AS ADVANCED A TECHNOLOGY AS InSb	1982
LONG WAVE IR ARRAYS MERCURY CADMIUM TELLURIDE 8 TO 14 μM LEAD TIN TELLURIDE 8 TO 14 μM	80K OPERATION; INITIAL DEVELOPMENT UNDERWAY	1984
CRYOGENIC REFRIGERATORS 2 YR. LIFETIME AT 80K	MAJOR NASA PROGRAM UNDERWAY	1981
WIDE FIELD REFLECTIVE OPTICS 2° TO 15° FIELD-OF-VIEW .4 μM TO 12 μM 10 TO 30 METER RESOLUTION	START DEVELOPMENT PROGRAM FY 81 FOR LARGE APERTURE (1 METER) DESIGNS	1983

Figure 3.3.14

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3.4 SENSOR ENGINEERING CONSIDERATIONS
MR. WILLIAM MEYER

I. OVERVIEW

a. Experiment Objectives - see Section 3.2 (Figure 3.2.3)

b. General Mission Description - see Section 3.2

II. SYSTEM REQUIREMENTS - Figure 3.4.1

a. Configuration - the MRS is being designed to fit into the space alloted to the MSS on a Landsat D type mission. This places size, shape and weight constraints on the design.

b. Orbit - the MRS (on a Landsat D type mission will fly in a sun synchronous orbit at an altitude of 705 km (440mi) with a 9:30 a.m. equator crossing time.

c. Spatial Coverage - see Figure 3.2.9.

d. Registration - the detectors are to be aligned to a precision of ± 0.1 of a pixel with a cumulative error over the length of the array of less than ± 0.5 of a pixel.

e. Square Wave Response - 500 m at 1.00 MTF sq. to 15 m at 0.30 MTF sq. (MTF = Modulation Transfer Function).

f. Alignment - the instrument will be aligned to a precision of $\pm 0.1^{o}$.

g. Boresight Pointing - $\pm 40^{o}$ in the cross-track direction
- $\pm 55^{o}$ in the along-track direction.

h. Spectral Coverage - there will be four arrays each of which is sensitive in the .35 to 1.0 range. Each of the four arrays will have five separate spectral filters which will be selectable by command while in orbit.

i. Radiometric Requirements - the MRS design is for 0.5% sensitivity (0.005 $NE\Delta\rho$) for a variety of spectral bands and a variety of scene conditions.

MULTISPECTRAL RESOURCE SAMPLER (MRS)
(PROVIDES AGRICULTURAL REPEAT COVERAGE AND STEREO)

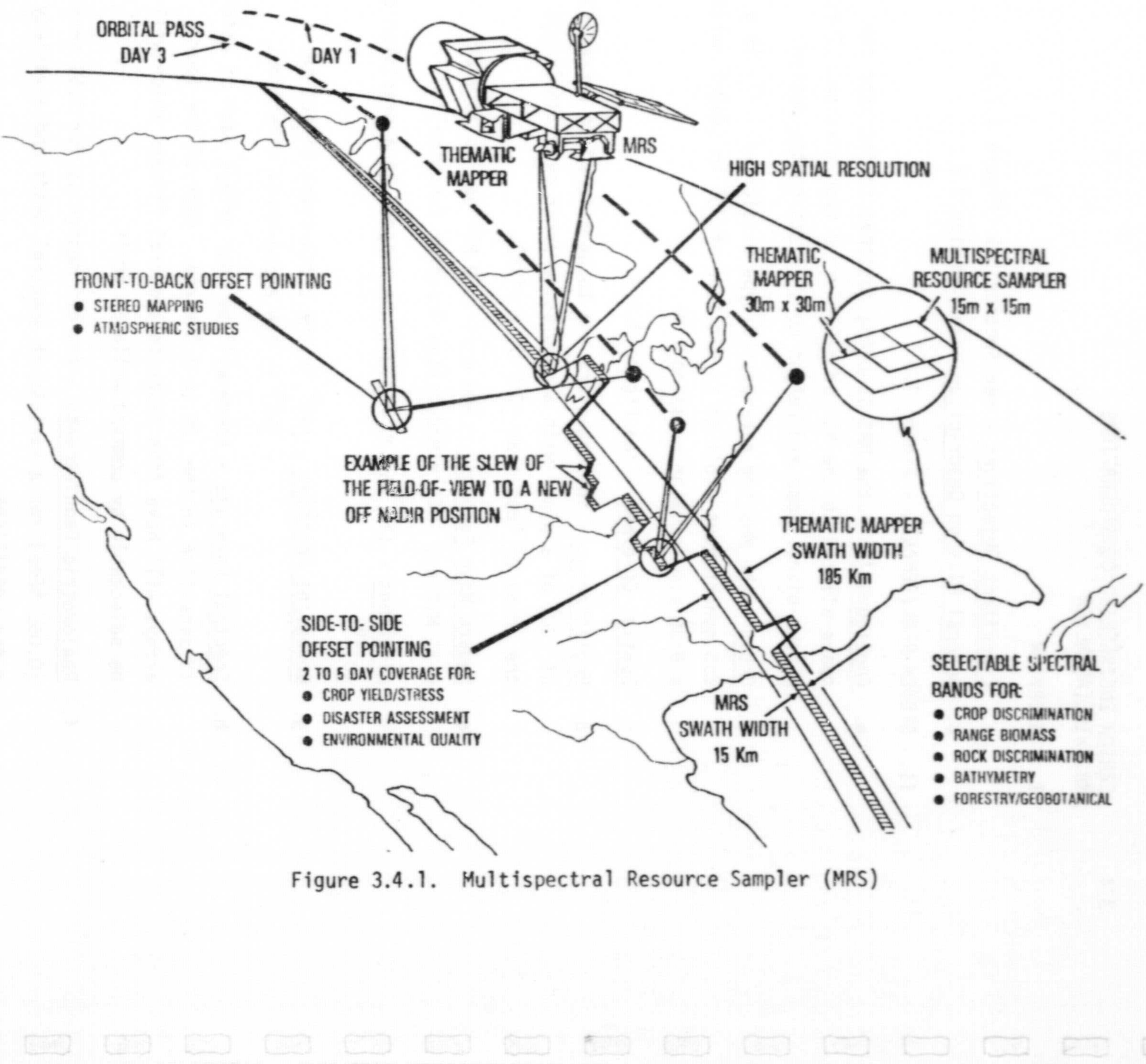

Figure 3.4.1. Multispectral Resource Sampler (MRS)

III. BASELINE SUBSYSTEMS

a. Optics

1. Telescope Objective - all reflective optics; 70 cm focal length; 20 cm diameter

2. Spectral Filters - see Figure 3.2.8. on Page 3-17.

b. Focal Plane Assembly (Figure 3.4.2)

1. Detectors - four discrete linear arrays of 2000 detectors/array

2. Signal processing - Figure 3.4.2 shows the general scheme of the basic signal processing.

c. Structures & Mechanisms

1. Structure - Volume 64 cm x 74 cm x 156 cm
   - Weight 70 kg.

2. Pointing/Slewing Mechanisms
   - cross-track pointing of $\pm 40^{\circ}$
     slew rate of 30°/sec.
   - along track pointing of $\pm 55^{\circ}$
     slew rate 5°/sec.

3. Optical Filter Mechanisms - four filter wheels, one for each array. Each filter wheel will contain five filters, and each wheel will be indexed independently.

d. Electronics (Figure 3.4.3)

1. High data rate electronics

2. Telemetry & Command - 15 Megabits/sec. via RIU.

3. Power Supply & Conditioning - power requirements include unregulated, multiple regulated & low noise/high regulated power supplies for a total of 85 watts.

e. Test & Calibration Equipment (Figure 3.4.4)

1. Electronic and Recording

2. Optical Simulation

3. Instrument Ground Control

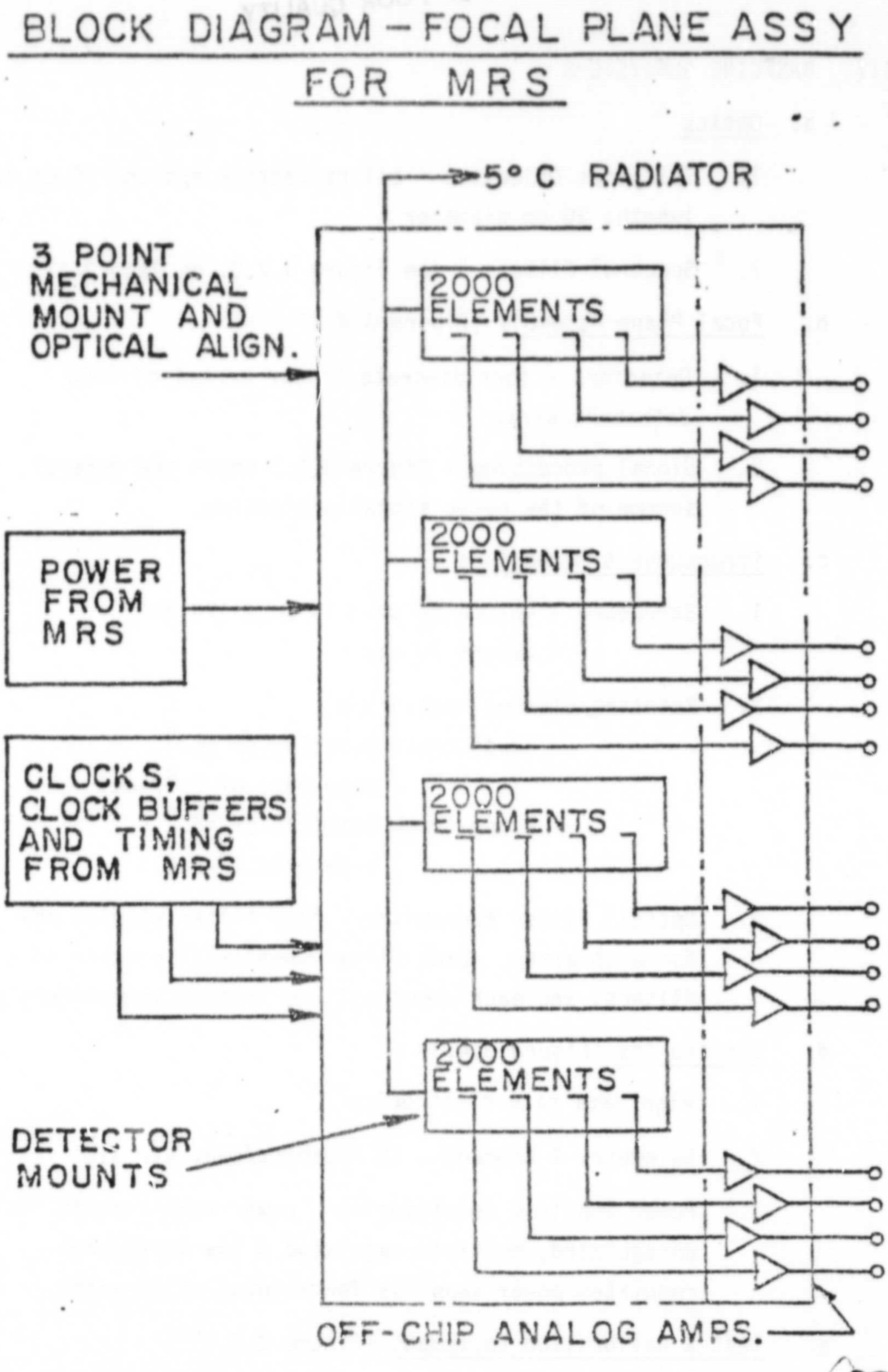

Figure 3.4.2. Block Diagram-Focal Plane Assy for MRS

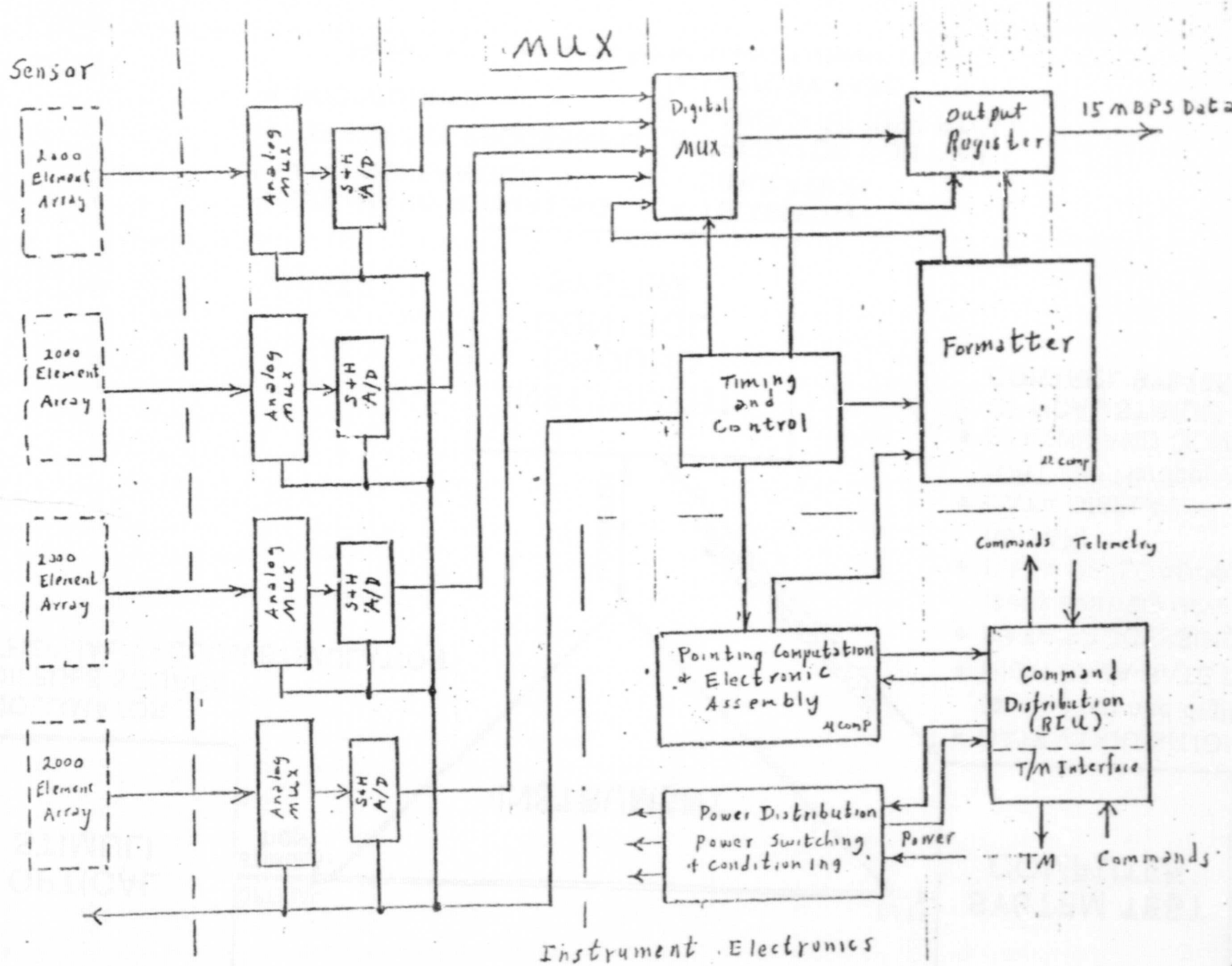

Figure 3.4.3. Instrument Electronics

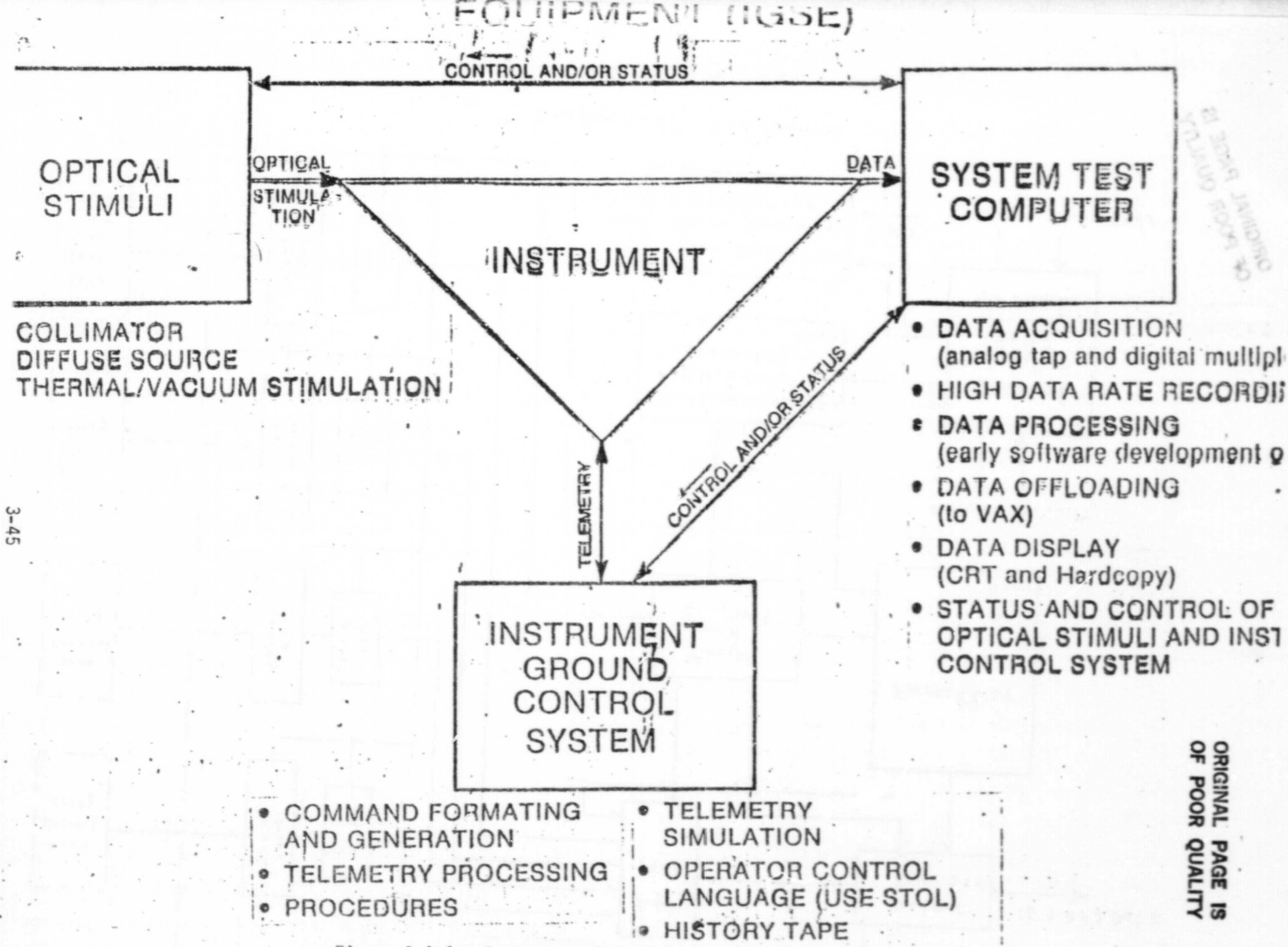

Figure 3.4.4. Instrument Ground Support Equipment (IGSE)

f. Thermal Requirements Definition

1. Focal Plane Assembly will be maintained at 5°C with a tolerance of ±0.5°C.

2. The bulk of the instrument will be maintained at 20°C with a tolerance of ±5°C.

IV. TEST AND CALIBRATION PHILOSOPHY

a. System Level Tests

b. Subsystem Level Tests

c. Environmental Tests

d. Calibration

1. Ground Calibration

2. On-Board Calibration.

3.5 BIDIRECTIONAL REFLECTANCE STUDIES & THE POTENTIAL OF MRS

DR. JAMES SMITH

I. Definitions

Bidirectional reflectance refers to a very specific type of measurement of reflectance. The bidirectional reflectance ρ is related to the measurement of reflected natural light by the equation given in Figure 3.5.1. In this equation, the first term on the right hand side is the radiance received at the sensor due to the solar irradiance reflected by the target into the sensor. This term is dependent upon the solar zenith angle as well as the directional reflectance characteristics of the target. The second term on the right hand side is the radiance received at the sensor due to the target reflectance of skylight. As it is written here, there are no apriori assumptions about the angular distribution of skylight or about the directional reflectance characteristics of the target. Atmospheric effects are not accounted for in this equation which refers to measurements made at ground level. If the solar irradiance, $E(\hat{k}_0)$, and skylight radiance distribution $E(\hat{k}')$ are known, measured or approximated with reasonable accuracy, then measurements of the reflected radiance, $L(\hat{k})$, will yield information about the target which is contained in ρ.

There are more than just a few other concepts and terms connected with reflectance, several of which are listed in Figure 3.5.2. This diversity leads to some confusion about the exact meaning of bidirectional reflectance and how it is measured. "The truth" is the equation of Figure 3.5.1. There are a few who have seen the mysterious light in the castle keep (Figure 3.5.3) and who are guardians of "the truth." There are also those outside the castle keep who are working with half-truths and incomplete information. There are even a few gypsies outside castle walls selling their own curious wares.

All this is simply to emphasize that not only are there many different data collection methods but there are varying degrees of understanding of these methods and their meanings. One must be cautious when reading the literature or using another's data.

$$L(\hat{K}) = \frac{1}{\pi} E(\hat{K}_0)\rho(\hat{K}, \hat{K}_0)\cos\Theta_{\hat{K}_0} + \frac{1}{\pi}\iint E(\hat{K}')\rho(\hat{K}, \hat{K}')\cos\Theta_{\hat{K}'}\, d\omega'$$

L = radiance

E = irradiance

ρ = reflectance

$\hat{K}$ = sensor angle

$\hat{K}_0$ = sun angle

$\hat{K}'$ = sector angle

FIGURE 3.5.1.

"REFLECTANCE GANG"

BI-DIRECTIONAL

BI-CONICAL

BI-HEMISPHERICAL

HEMISPHERICAL-DIRECTIONAL & V.V.

HEMISPHERICAL-CONICAL & V.V.

REFLECTANCE FACTORS VS DISTRIBUTION

FIELD VS LABORATORY

APPARENT DIRECTIONAL REFLECTANCE

EQUIVALENT LAMBERTIAN REFLECTANCE

FIGURE 3.5.2. REFLECTANCE GANG

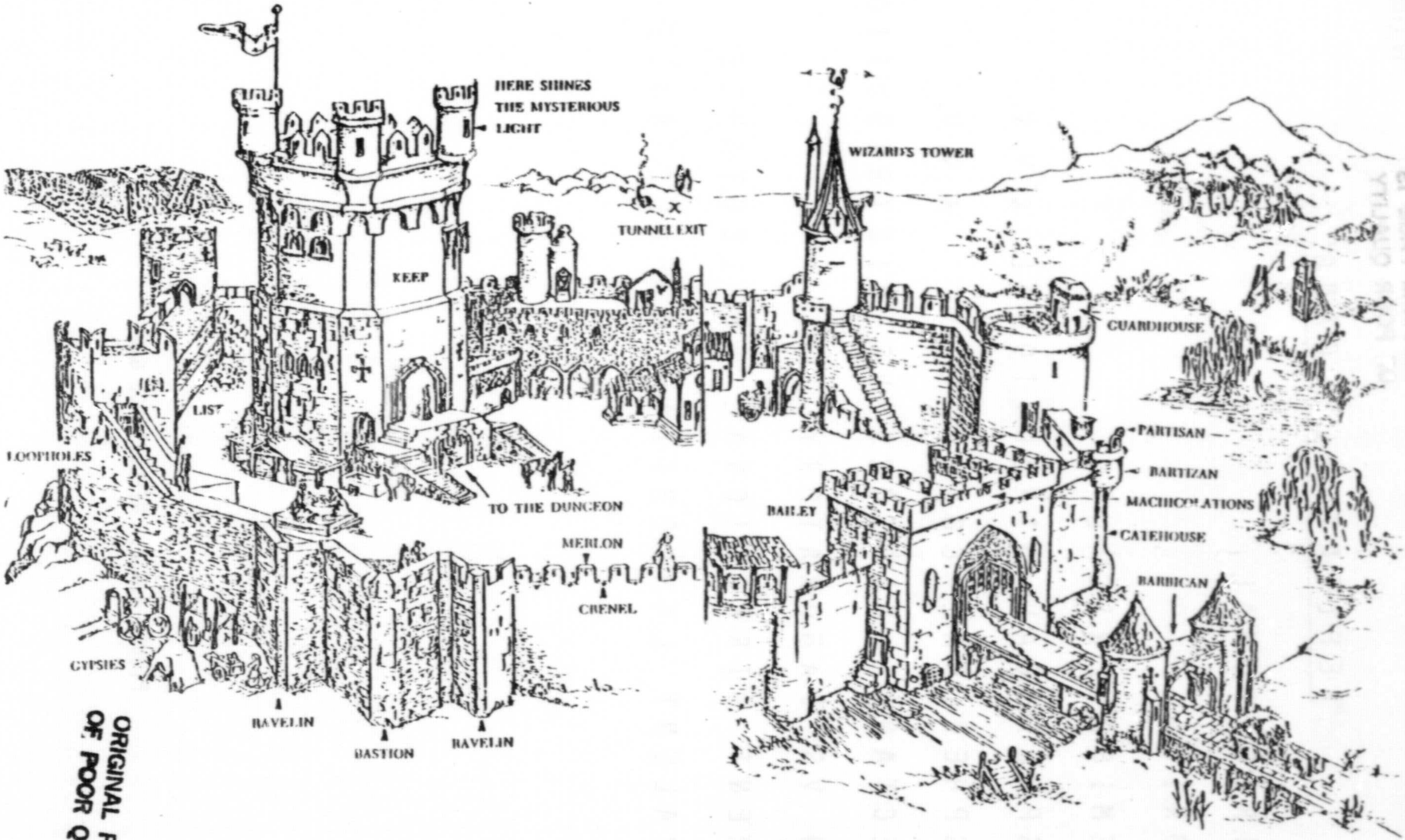

FIGURE 3.5.3. CASTLE KEEP

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II. Status of Measurements

There is a wide variety of data sources available for both field and laboratory measurements. They vary widely in quality and in target type.. For the field measurements an outstanding source is Kriebel whose published work is limited but excellent (Figure 3.5.4). The Lacie program has generated a large collection of field measurements which also contain useful ancillary data. "Typical" values of reflectance signatures are also available for a wide variety of materials from ERIM. Besides these there are many miscellaneous references mostly from the late 60's and 70's. For many of these some interpretation may be required before the data will be useful. As an example of the data available, two sets of curves from Kriebel (Kriebel, K.T., 1978 Measured Spectral Bidirectional Reflection Properties for Four Vegetated Surfaces. Applied Optics 17(2): 253-259) are included in Figures 3.5.5 and 3.5.6; these curves show the angular variation in reflectance of pasture land and coniferous forest respectively at several solar zenith angles.

Figure 3.5.7 is a summary of information on surface reflectance (field) measurements. There is a large data base for crops. For other targets there are only limited observations. One must be cautious in using these measurements since the assumptions and types of measurements will vary from source to source.

III. Status of Theory

There are a variety of remote sensing models for vegetation reflectance (Figure 3.5.8). Suit's (1972) model is perhaps the most widely used. A more recent and very impressive model is that of Bunnik (1977). There are more models than those listed in Figure 3.5.8. Most of the models are intended for crops and grasses with limited applications to forests (Figure 3.5.9). Given the "appropriate" inputs, all perform reasonably well. The "appropriate" inputs, however, may not be available or may not be practical to measure. There is a need to extend the modelling to more difficult situations.

FIELD MEASUREMENTS

KRIEBEL - (LIMITED, BUT EXCELLENT)

LACIE (LARS ARCHIVE - EXHAUSTIVE
(CROPS) GOOD ANCILLARY DATA,
MOSTLY VERTICAL VIEW)

TARGET SIGNATURES (ERIM/JSC - GOOD
SOURCE OF "TYPICAL" VALUES
FOR WIDE VARIETY OF MATERIALS)

MISC*

ABOUT 70 REFERENCES, MOSTLY
LATE 60'S - 70'S.

E.G. COULSON, SALOMONSON, ...
(WHITE SANDS?)

- INTERPRETATION REQUIRED

FIGURE 3.5.4. FIELD MEASUREMENTS

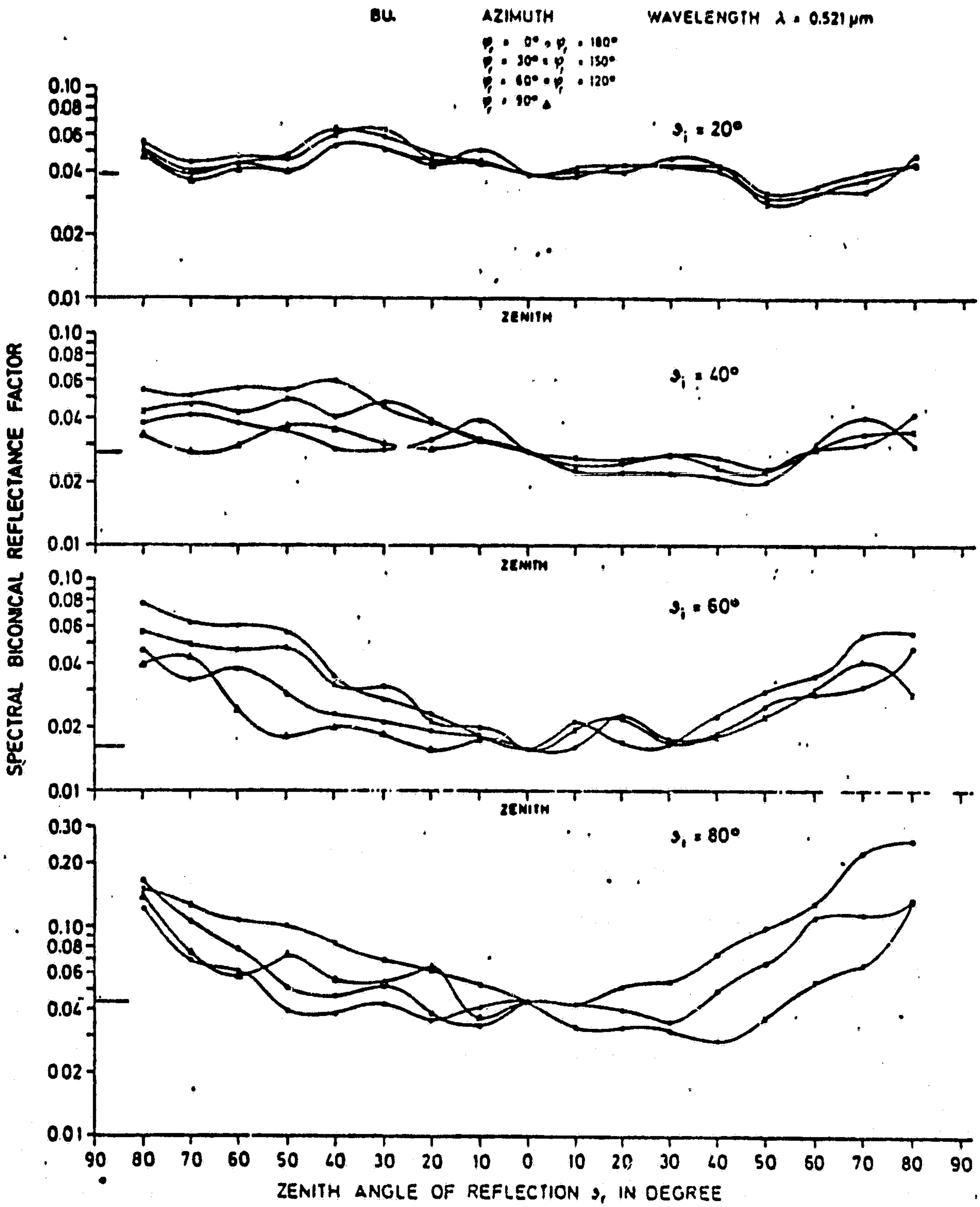

Fig. 3. Same as Fig. 1 but for pasture land.

FIGURE 3.5.5. SPECTRAL BICONICAL REFLECTANCE FACTOR

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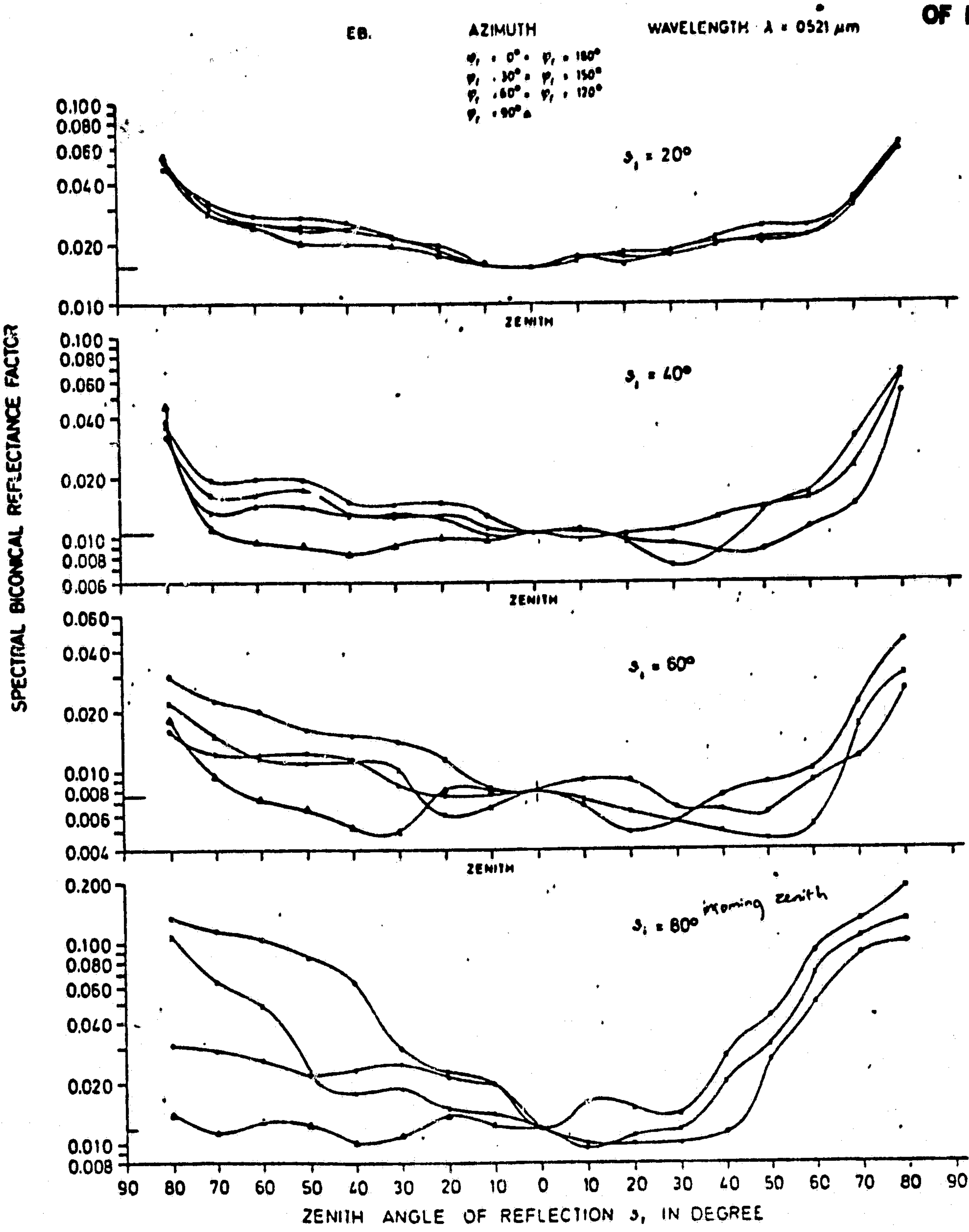

Fig. 4. Same as Fig. 1 but for coniferous forest.

FIGURE 3.5.6. SPECTRAL BICONICAL REFLECTANCE FACTOR

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SUMMARY (SURFACE ONLY)

* GOOD DATA ON CROPS
* LIMITED OBSERVATIONS OTHERWISE
* MEASUREMENTS MAY BE DANGEROUS
* FOR ZENITH SUN/VIEW ANGLES LESS THAN 30 DEGREES, LAMBERTIAN ASSUMPTION "REASONABLE"
* PATHOLOGICAL STATES

  VARIABLE IRRADIANCE (SPATIAL, ANGULAR)

  MIXTURES

  TOPOGRAPHY OFTEN INDUCES LARGE EFFECTIVE SOURCE/VIEW ANGLES

FIGURE 3.5.7. SUMMARY (SURFACE ONLY)

REMOTE SENSING MODELS

(1970) ALLEN AND RICHARDSON

(1970) IDSO AND DEWIT

(1972) SUITS

(1972) SMITH AND OLIVER

(1976) EGBERT AND ULABY

(1977) BUNNIK

OTHERS

FIGURE 3.5.8. REMOTE SENSING MODELS

SUMMARY (MODELS)

APPLIED MOSTLY TO CROPS, GRASSES

LIMITED APPLICATION TO FORESTS

GIVEN "APPROPRIATE" INPUTS ALL PERFORM REASONABLY WELL

GOOD FOR DESIGN STUDIES AND GEDANKEN EXPERIMENTS

LITTLE WORK DONE ON THE INVERSE OR INDIRECT SENSING PROBLEM (E.G. FOREST AND BIOMETEOROLOGISTS-NORMAN)

NEED TO EXTEND TO MORE DIFFICULT MODELING SITUATIONS

FIGURE 3.5.9. SUMMARY (MODELS)

IV. MRS Implications

Some data is available which suggests that multiple viewing angles are useful for distinguishing among crops. For instance, there are data available for crops in Kansas for solar zenith angles between 30^{o} and 70^{o} and for viewing angles from 0^{o} to 40^{o}. (Figure 3.5.10) The objectives of using multiple viewing angles would be to (1) aid in scene normalization, for example, using the differences in atmospheric path length to improve the atmospheric correction and (2) improve the discrimination among targets using their directional reflectance characteristics (Figure 3.5.11).

One possibility is suggested by the graphs in Figures 3.5.12 and 3.5.13. Figure 3.5.12 shows that crops differing in canopy geometry exhibit the same mean leaf projection at 57^{o} and hence should exhibit similar directional reflectance properties at this angle. In fact, a "cross-over" point is shown at this angle in both. Figures 3.5.12 and 3.5.13. Differences in measured reflectance at this angle should arise primarily from crop leaf-area or biomass. This is further verified by the graphs in Figure 3.5.14 which shows that the maximum divergence between two canopies differing only in leaf-area in feature selection using the best two wavelengths (out of a possible 7) occurs for observation angles near 55^{o}.

We do not really know how much will be gained by having multiple observation angles, nor is it clear exactly where the improvements will come. We are still in the workshop (Figure 3.5.15) and there is much work to be done before we will be certain about how this tool should be used.

MRS IMPLICATIONS

E. G. KANSAS

SOLAR ZENITH ANGLES	30-70 DEGREES
VIEWING ANGLE	0-40 DEGREES

FIGURE 3.5.10. MRS IMPLICATIONS

OBJECTIVES:

1. SCENE NORMALIZATION

2. INCREASED DISCRIMINATION

FIGURE 3.5.11. OBJECTIVES

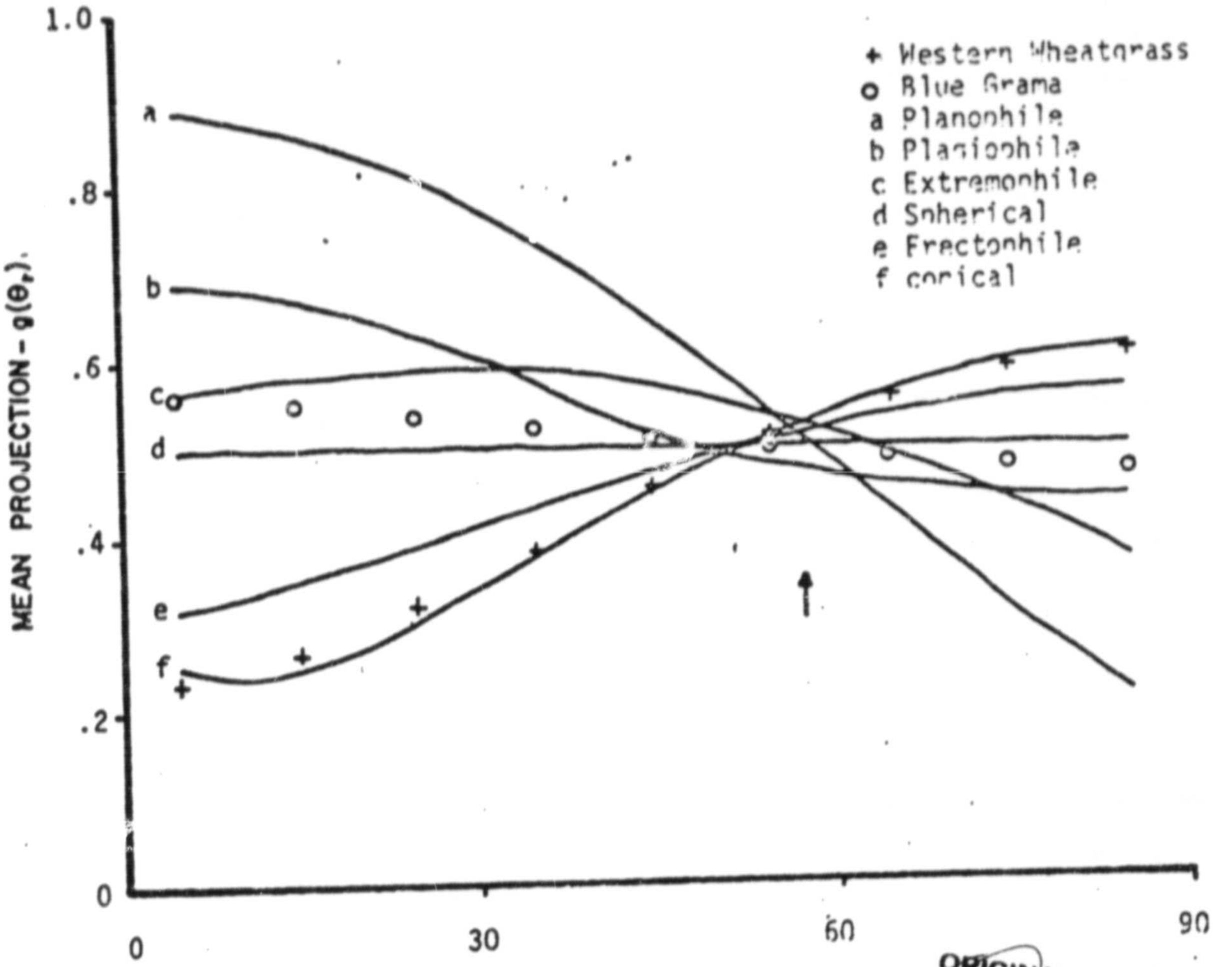

FIGURE 3.5.12. MEAN PROJECTION OF A LEAF ELEMENT FOR EACH OF THE CANOPY TYPES SHOWN IN FIGURE 4.

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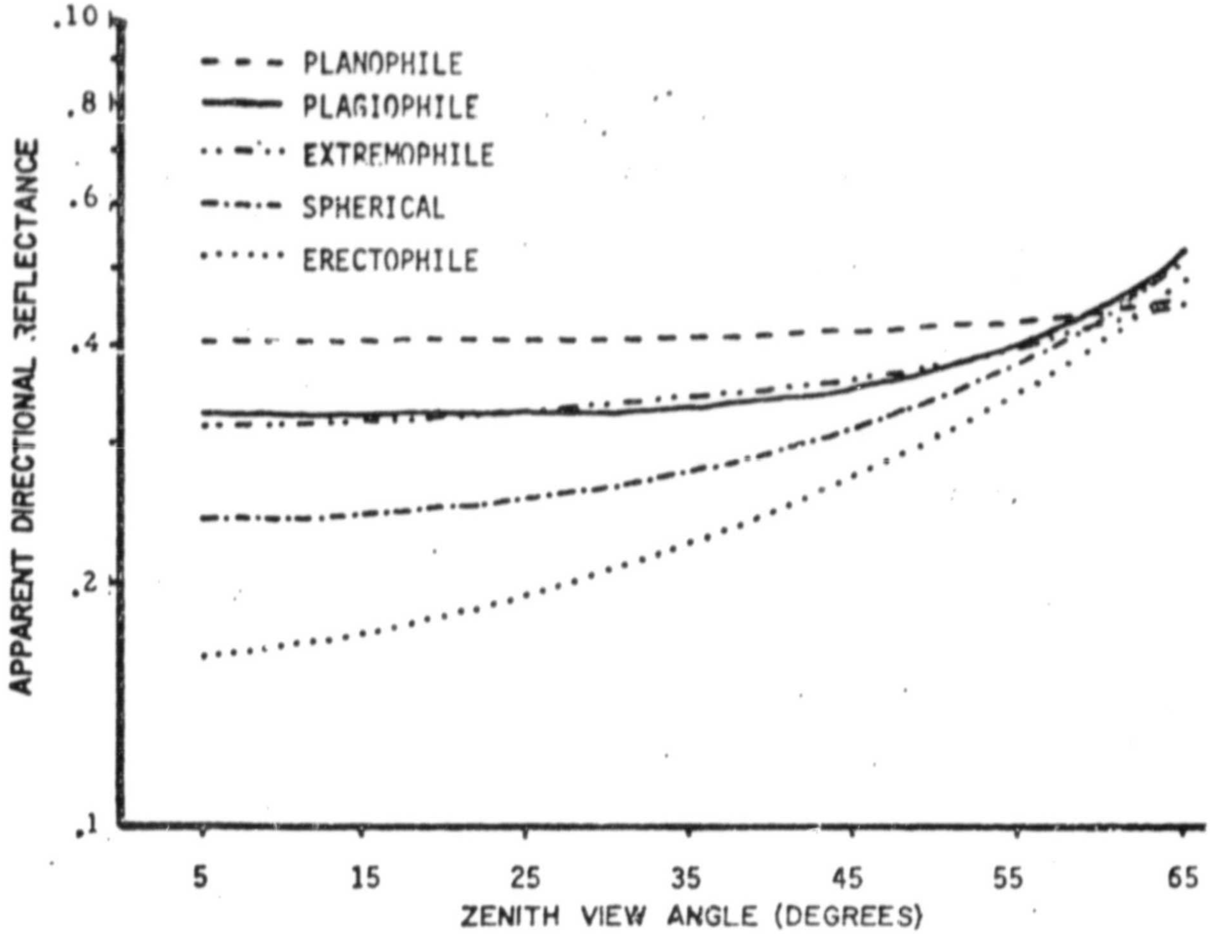

FIGURE 3.5.13. PREDICTED APPARENT DIRECTIONAL REFLECTANCE FOR THE CANOPY TYPES SHOWN IN FIGURE 4.

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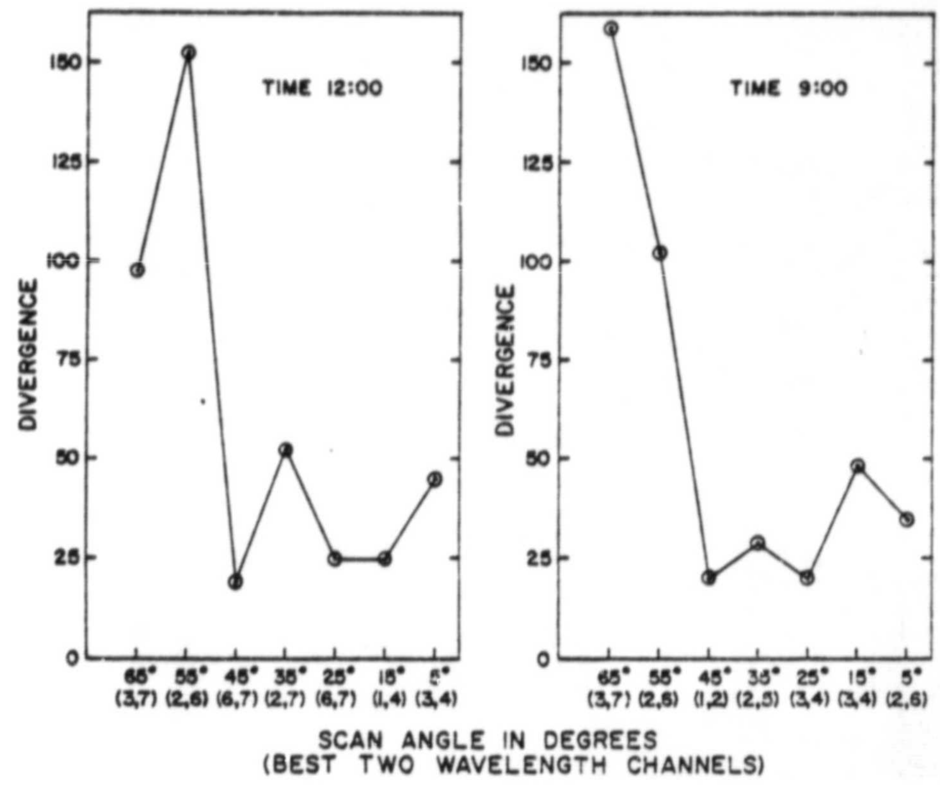
CHANGES IN FEATURE SELECTION



Variation in maximum divergence with scan angle and best two wavelengths out of seven. Results are given for 12:00 (solar zenith angle 22.3 degrees) and 9:00 (solar zenith angle 44.5 degrees) computer simulations.

FIGURE 3.5.14. CHANGES IN FEATURE SELECTION

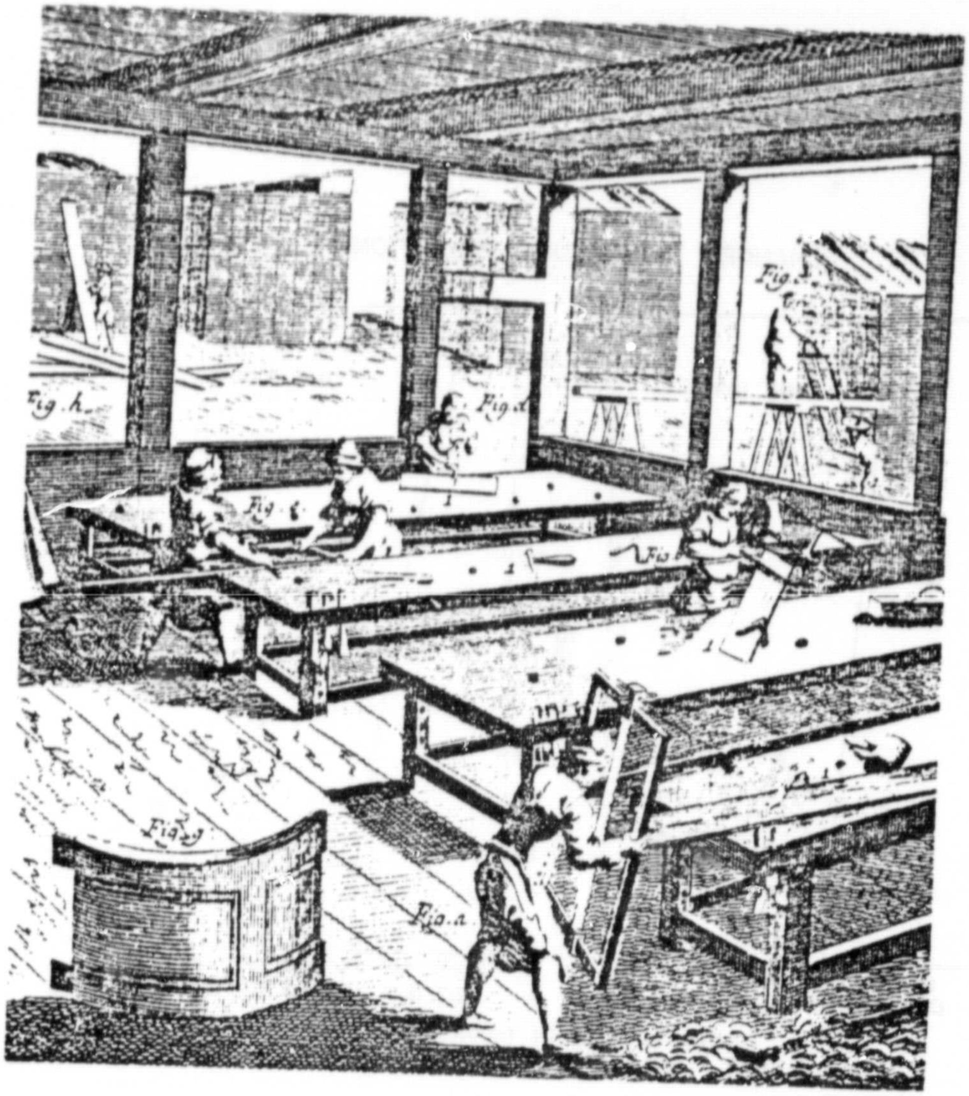


FIGURE 3.5.15. WORKSHOP

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3.6 ATMOSPHERIC CORRECTION ALGORITHMS FOR THE REMOTE SENSING OF THE EARTH'S SURFACE

DR. ROBERT TURNER

There are three physical processes by which the atmosphere will affect remote sensing measurements at the earth's surface (Figure 3.6.1): scattering, absorption and thermal emission. Radiation may be attenuated due to scattering and absorption by the atmosphere (transmittance loss), leading to a reduction of the measured signal. Scattering by gasses and particulates in the atmosphere will account for part of the remote spectral measurements (path or sky radiance) in the wavelength range from ~0.34 μm to 3.0 μm. Finally, thermal emission by gasses and particulates in the atmosphere will contribute to the remote measurements (path or sky radiance) in the 3.0 μm to 15 μm wavelength region. Figure 3.6.2 illustrates these effects.

In the following discussion we will cover some of the more important concepts involved in the atmospheric effect on remotely sensed data. Figure 3.6.3 lists the most important quantities used in the discussion along with the symbols used. Also listed (in Figure 3.6.4) are the fundamental parameters which contribute to the atmospheric effect on radiation.

The MRS has several advantages for atmospheric investigations that have been available on previous satellite systems (Figure 3.6.5).

(1) The spectral range extends into the UV (0.36μm); the atmospheric scattering is stronger in the UV/blue region of the spectrum.

(2) The spatial resolution is better (15m). This allows for smaller targets.

(3) It will be possible to make multiple-angle views of selected targets.

This last capability is illustrated in Figure 3.6.6. Viewing through different atmospheric path lengths will aid in making atmospheric corrections.

The basic remote sensing equation is given in Figure 3.6.7. The radiance at the sensor, L. consists of radiation at the target, L_0, which has been transmitted through the atmosphere, T, plus the path radiance, Lp. The radiance at the target is due to the reflectance by the target of solar radiance,

PHYSICAL PROCESSES IN REMOTE SENSING ANALYSIS

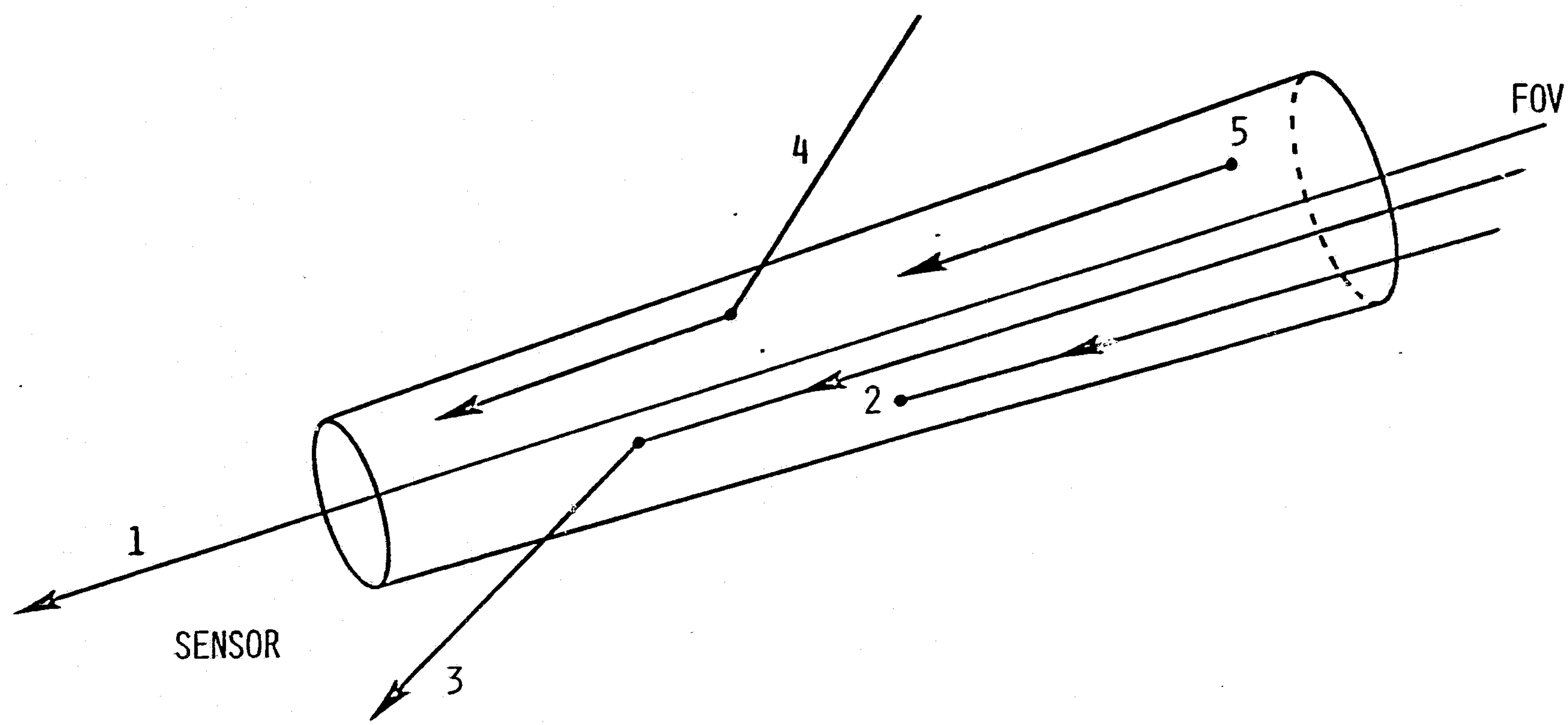
- ATTENUATION OF RADIATION BY SCATTERING AND ABSORPTION (TRANSMITTANCE LOSS)

- MULTIPLE SCATTERING BY GASES AND PARTICULATES (PATH RADIANCE, SKY RADIANCE); IMPORTANT FOR $\sim 0.34\mu M$ - $3.0\mu M$

- THERMAL EMISSION BY GASES AND PARTICULATES (PATH RADIANCE, SKY RADIANCE); IMPORTANT FOR $\sim 3.0\mu M$ - $15\mu M$

Figure 3.6.1. Physical Processes in Remote Sensing Analysis

INTERACTION MECHANISMS



1. NON-INTERACTING RADIATION (NO GAIN, NO LOSS)
2. ABSORBED RADIATION (LOSS)
3. SCATTERED RADIATION (LOSS)
4. SCATTERED RADIATION (GAIN)
5. EMITTED RADIATION (GAIN)

Figure 3.6.2. Interaction Mechanisms

IMPORTANT QUANTITIES FOR REMOTE SENSING

λ	~ WAVELENGTH OF RADIATION
θ_0	~ SOLAR ZENITH ANGLE
φ_0	~ SOLAR AZIMUTH ANGLE
θ	~ NADIR VIEW ANGLE
φ	~ AZIMUTH VIEW ANGLE
$\tau_0(\lambda)$	~ OPTICAL THICKNESS
$\omega_0(\lambda)$	~ SINGLE-SCATTERING ALBEDO
$\Phi(\mu,\varphi,\mu',\varphi')$	~ SINGLE-SCATTERING PHASE FUNCTION
$\rho(\mu,\varphi,\mu',\varphi')$	~ BI-DIRECTIONAL SURFACE REFLECTANCE
$\rho(\lambda)$	~ SURFACE ALBEDO
$E_0(\lambda)$	~ EXTRATERRESTRIAL SOLAR IRRADIANCE
$E_S(\lambda)$	~ SOLAR IRRADIANCE AT TARGET
$E_T(\lambda)$	~ TOTAL OR GLOBAL IRRADIANCE AT TARGET
$L_P(\lambda)$	~ PATH RADIANCE
$L_D(\lambda)$	~ DIFFUSE IRRADIANCE AT TARGET

Figure 3.6.3. Important Quantities for Remote Sensing

FUNDAMENTAL PARAMETERS

P	~	ATMOSPHERIC PRESSURE AT TARGET
$T(z)$	~	ATMOSPHERIC TEMPERATURE PROFILE
D_{O3}	~	OZONE DENSITY VERTICAL PROFILE
ρ_v	~	ABSOLUTE HUMIDITY
f	~	RELATIVE HUMIDITY
$\psi(r)$	~	AEROSOL SIZE DISTRIBUTION
$m(\lambda)$	~	AEROSOL INDEX OF REFRACTION
$N(z)$	~	AEROSOL NUMBER DENSITY
U	~	WIND SPEED
C	~	CLOUD COVER
A	~	SOLAR AUREOLE

Figure 3.6.4. Fundamental Parameters

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ADVANTAGES OF THE MULTISPECTRAL RESOURCE
SAMPLER (MRS) FOR ATMOSPHERIC INVESTIGATIONS:

- MULTI-ANGLE VIEWING OF SELECTED TARGETS
- SPECTRAL RANGE (0.36 μM - 1.0 μM); MULTIPLE SCATTERING
- SPATIAL RESOLUTION (15 METERS MAX.): SMALL TARGETS

Figure 3.6.5. Advantages of the Multispectral Resource Sampler (MRS) For Atmospheric Investigations

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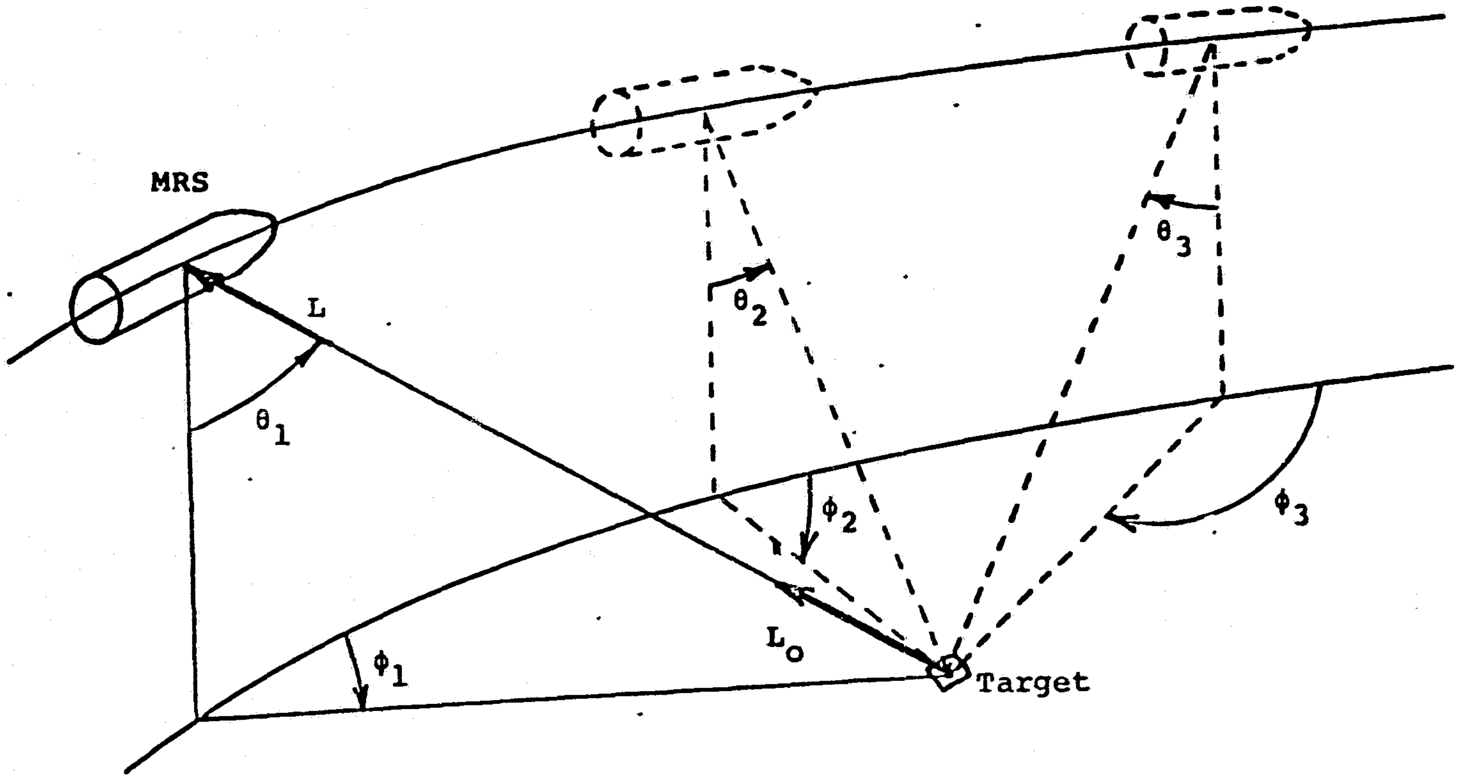

Figure 3.6.6. Variation of Nadir View Angle for the MRS for a Specific "Target"

REMOTE SENSING EQUATION

$$L(\tau,\mu,\varphi) = L_o(\tau_o,\mu,\varphi)T(\tau,\mu) + L_p(\tau,\mu,\varphi)$$

$L(\tau,\mu,\varphi)$ ~ RADIANCE AT SENSOR

$L_0(\tau_0,\mu,\varphi)$ ~ RADIANCE AT TARGET

$T(\tau,\mu)$ ~ TRANSMITTANCE ALONG PATH

$L_p(\tau,\mu,\varphi)$ ~ PATH RADIANCE

Figure 3.6.7. Remote Sensing Equation

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L_s, and the diffuse sky radiance, L_D. The remote sensing geometry is shown in Figure 3.6.8.

The transmittance factor, T, is dependent on the wavelength, the atmospheric path length and the atmospheric optical thickness (Figure 3.6.9). The atmospheric optical thickness is a measure of the extinction of light of a particular wavelength when passing vertically through the atmosphere. It is defined by the equation in Figure 3.6.10 as an integral of the volume extinction coefficient, K. The volume extinction coefficient includes both scattering and absorption effects; it may be broken down into two components: a Rayleigh coefficient, K_R, and an aerosol coefficient, K_A (Figure 3.6.11).

Figure 3.6.12 illustrates the radiation components in a scattering, absorbing atmosphere. The earth's surface is illuminated by direct solar radiation, L_{sun}, singly-scattered solar radiation, L_{sss}, and multiply-scattered solar radiation, L_{mss}. Part of this incident radiation is reflected in the direction of the sensor, L_o but is attenuated along the path radiance due to scattering of light into the path by the atmosphere: Singly-scattered path radiance, L_{ssp}, and multiply scattered path radiance, L_{msp}.

The amount of sky radiance incident on the earth's surface as well as its angular distribution varies tremendously with atmospheric conditions. This is illustrated in Figure 3.6.13, which shows the sky radiance for both a Rayleigh (clear) atmosphere and for a hazy atmosphere. The reflected radiation, shown in Figure 3.6.13 as total radiance, also varies in intensity and distribution as the atmospheric characteristics vary. Figures 3.6.14 and 3.6.15 are alternate graphic views of this same phenomenon. The top graph on Figure 3.6.15 shows the dependence of path radiance on visual range and scan angle. The increase in brightness toward the horizon is called limb brightening. The path radiance can be minimized by making observations away from the sun and away from the horizon.

The total radiance at the sonsor is compared to the path radiance for various reflectances and optical thicknesses in Figure 3.6.16. An optical thickness of $\tau_o = 0.1$ corresponds to an extremely clear atmosphere while for $\tau_o = 10.0$, the atmosphere is optically infinitely deep. It should be clear from these graphs that the path radiance is both an important and highly variable component of the total radiance at the sensor.

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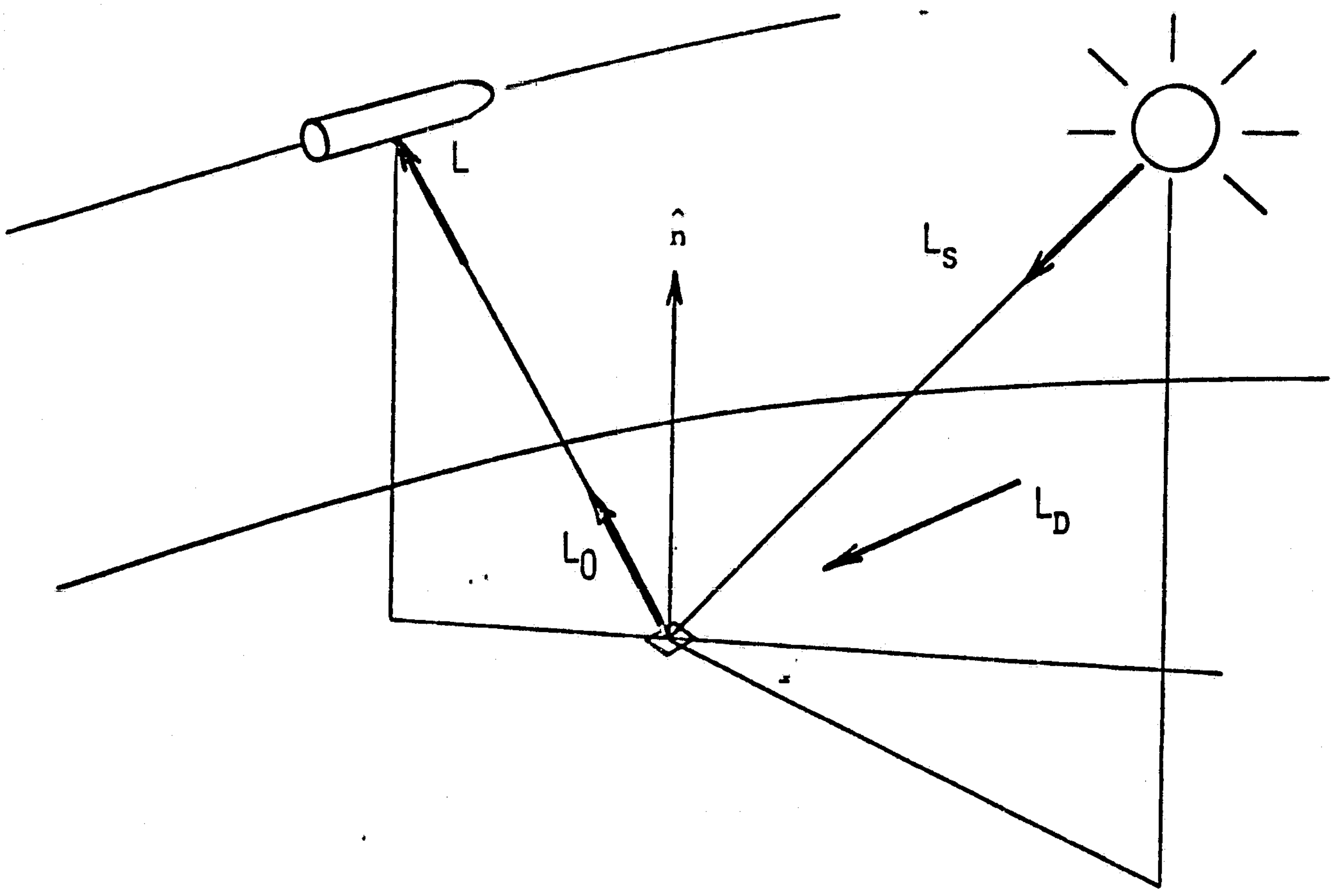


L ~ RADIANCE AT SENSOR

L_0 ~ RADIANCE AT TARGET

L_S ~ SOLAR RADIANCE

L_D ~ DIFFUSE RADIANCE

$\hat{n}$ ~ NORMAL TO SURFACE ELEMENT

REMOTE SENSING GEOMETRY

Figure 3.6.8. Remote Sensing Geometry

SPECTRAL TRANSMITTANCE

$$T(\lambda, \theta) \equiv e^{-\tau_0 \sec \theta}$$

$\lambda \sim$ WAVELENGTH

$\theta \sim$ NADIR VIEW ANGLE

Figure 3.6.9. Spectral Transmittance

ATMOSPHERIC OPTICAL THICKNESS

$$\tau_o(\lambda) \equiv \int_0^\infty \kappa(\lambda, Z)\, dZ$$

$\kappa(\lambda, Z)$ ~ VOLUME EXTINCTION COEFFICIENT (KM^{-1})

λ ~ WAVELENGTH

Z ~ ALTITUDE VARIABLE

Figure 3.6.10. **Atmospheric Optical Thickncss**

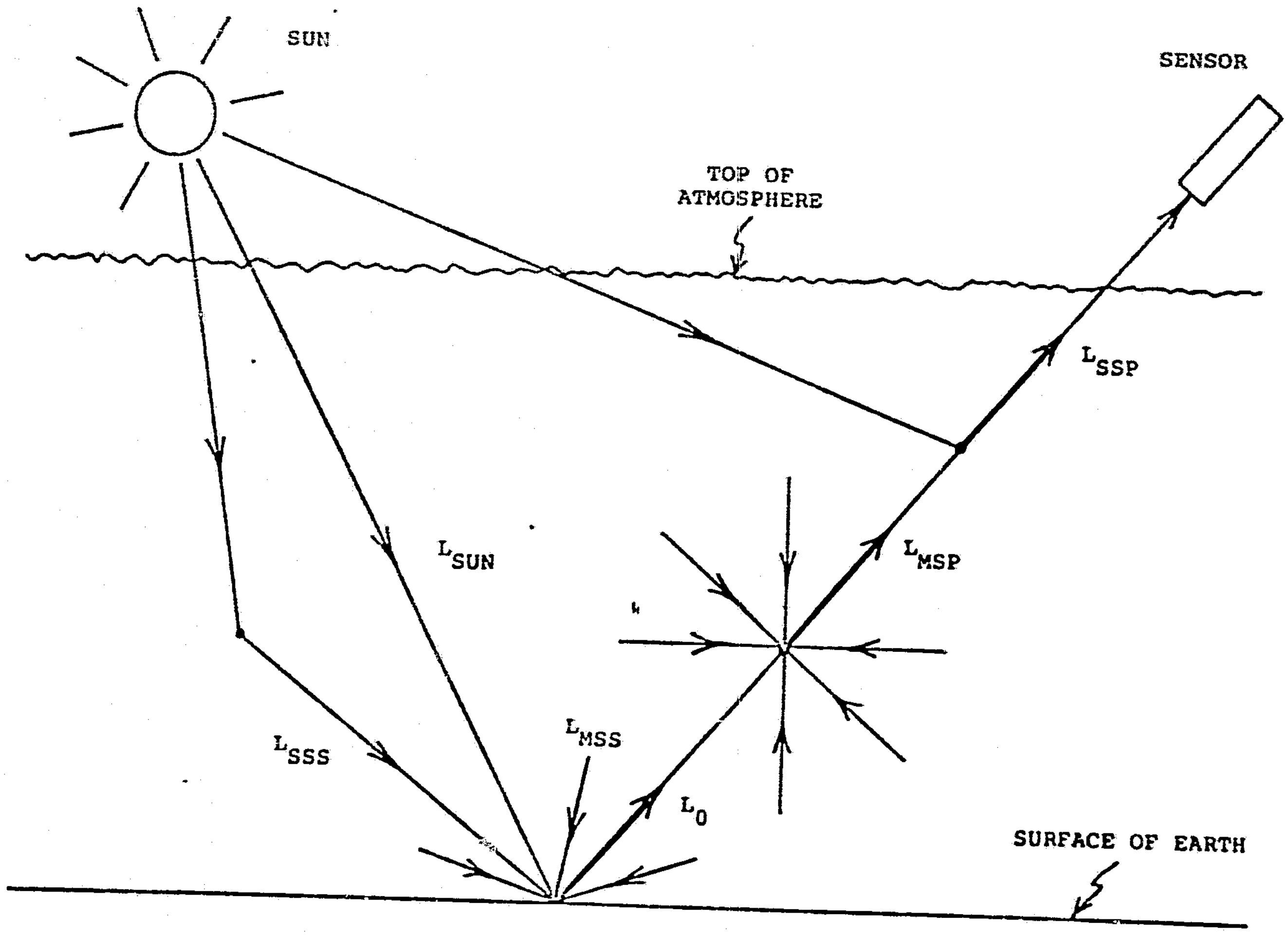
VOLUME EXTINCTION COEFFICIENTS

$$\kappa(\lambda, Z) = \kappa_R(\lambda, Z) + \kappa_A(\lambda, Z)$$

$\kappa_R(\lambda, Z)$ ~ RAYLEIGH COEFFICIENT (DEPENDS UPON WAVELENGTH, PRESSURE, AND ALTITUDE)

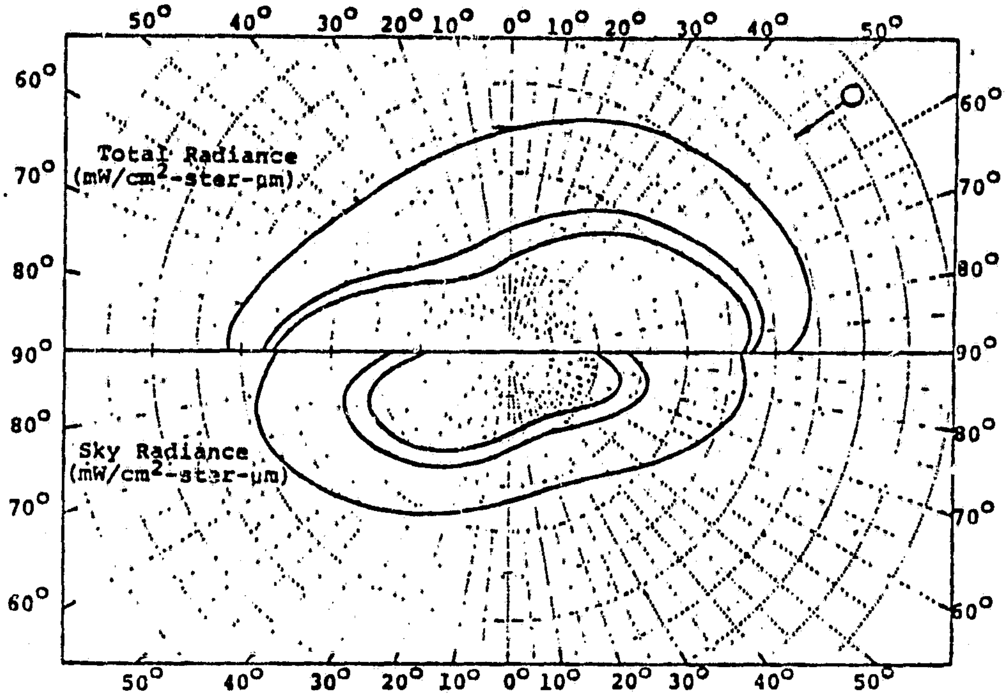
$\kappa_A(\lambda, Z)$ ~ AEROSOL COEFFICIENT (DEPENDS UPON WAVELENGTH, PARTICULATE SIZE, PARTICULATE NUMBER, PARTICULATE SHAPE, AND PARTICULATE REFRACTIVE INDEX)

Figure 3.6.11. Volume Extinction Coefficients

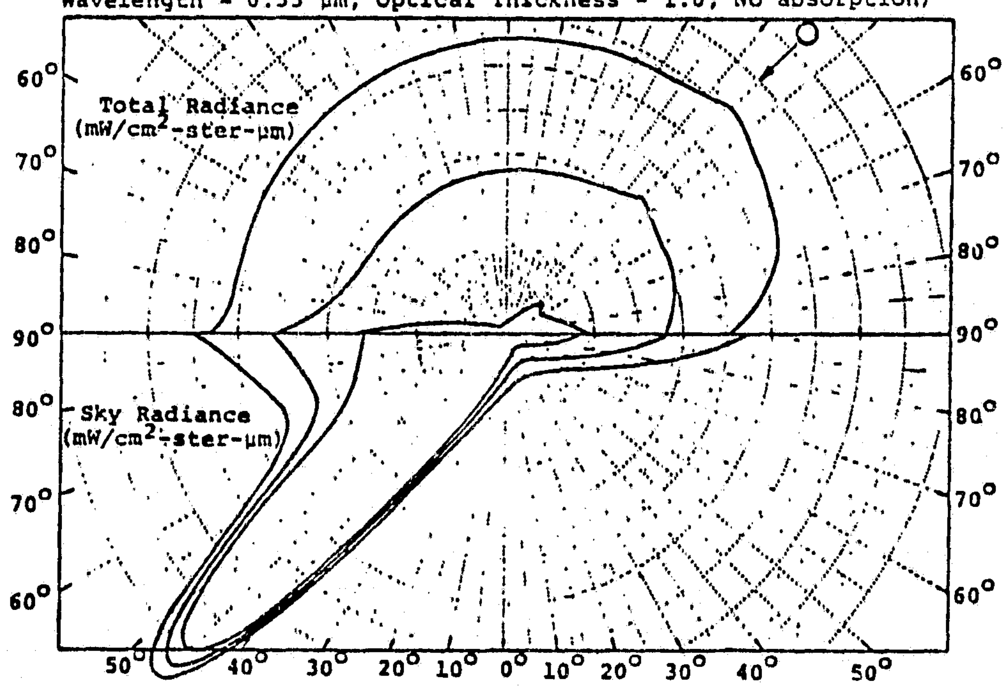


RADIATION COMPONENTS
(Radiation components in a scattering, absorbing atmosphere)

Figure 3.6.12. Radiation Components



RADIANCE IN A RAYLEIGH ATMOSPHERE
(Total and sky radiance as a function of view angle in the solar plane for surface reflectances of 0, 25, and 80 per cent. Solar zenith angle = 53°8', Wavelength = 0.55 μm, Optical Thickness = 1.0, No absorption)



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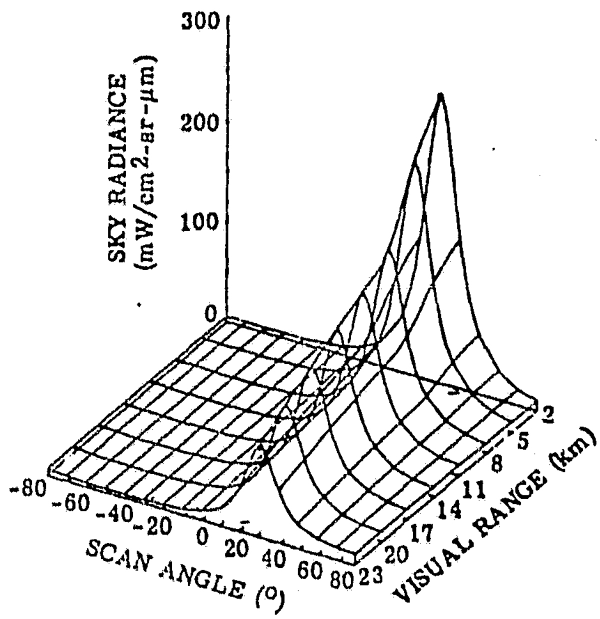
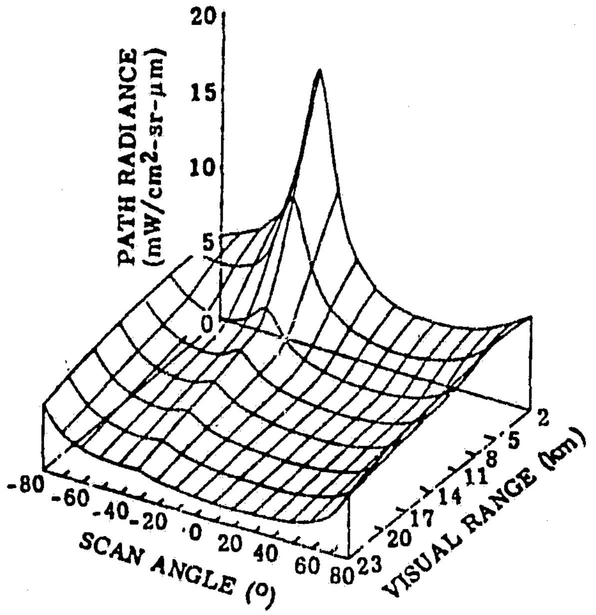
RADIANCE IN A HAZY ATMOSPHERE
(Total and sky radiance as a function of view angle in the solar plane for surface reflectances of 0, 50, and 90 per cent. Solar zenith angle = 45°, Wavelength = 0.55 μm, Optical Thickness = 0.2, No absorption)

Figure 3.6.13. Radiance in Rayleigh Atmosphere and Radiance in a Hazy Atmosphere

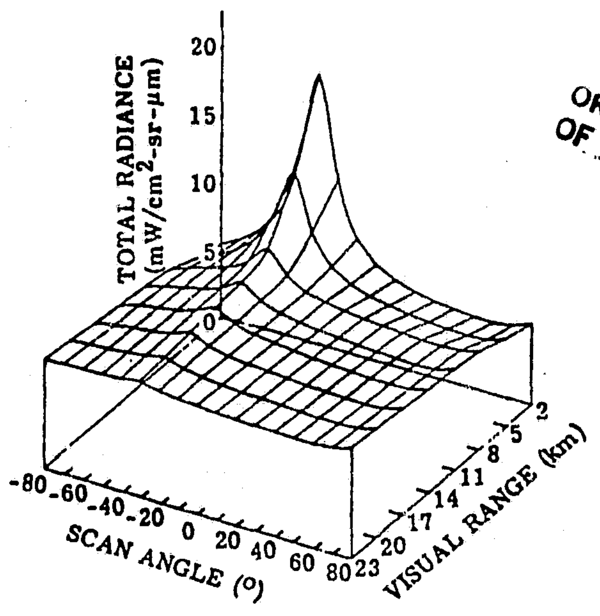


DEPENDENCE OF SKY RADIANCE ON VISUAL RANGE AND SCAN ANGLE. Solar zenith angle = 30°; wavelength = 0.55 μm; altitude = 0.1 km; azimuthal angle = 0° (in the plane of the sun); surface albedo for green vegetation.

Figure 3.6.14. Dependence of Sky Radiance on Visual Range and Scan Angle

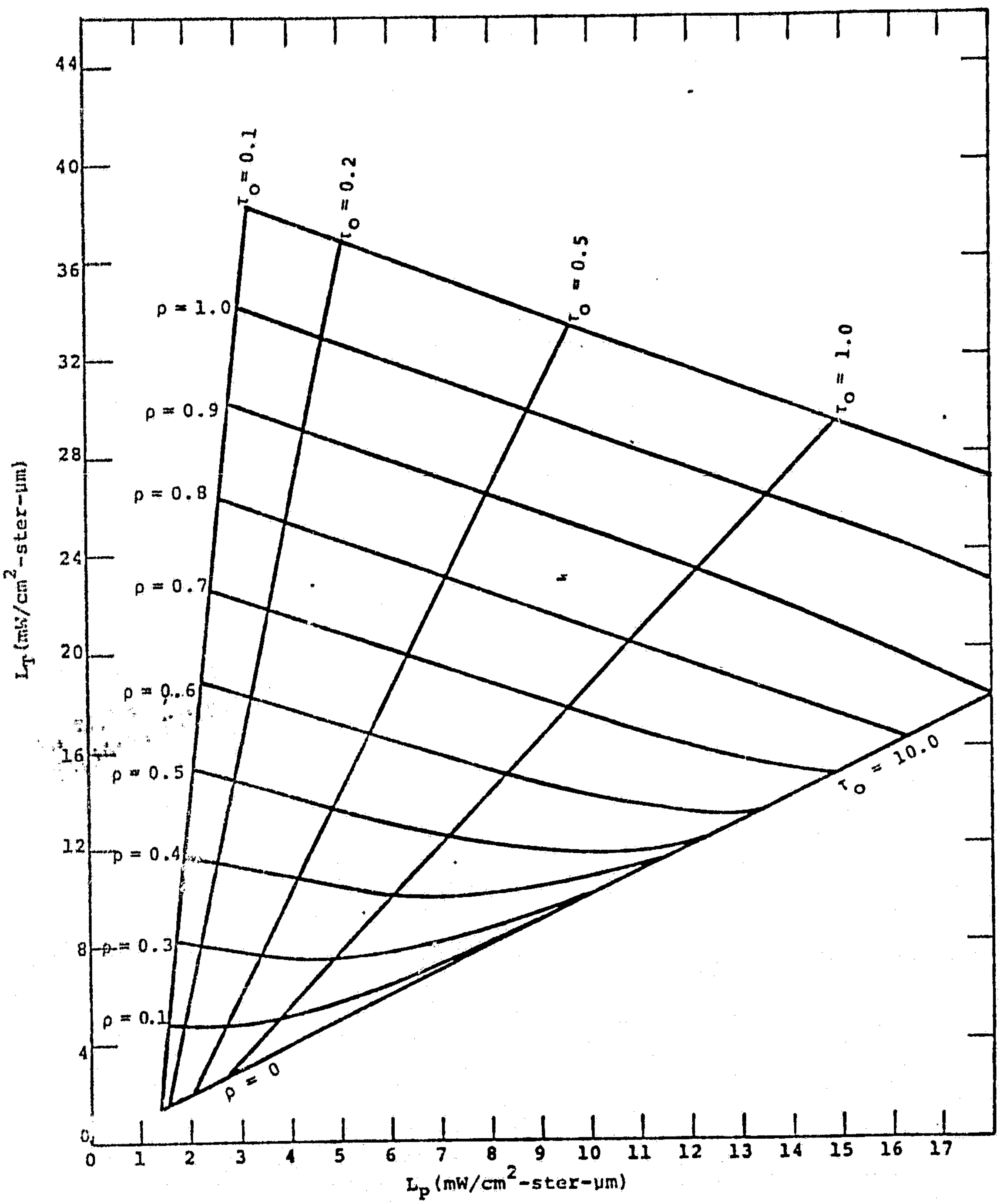


DEPENDENCE OF PATH RADIANCE ON VISUAL RANGE AND SCAN ANGLE. Solar zenith angle = 30°; wavelength = 0.55 μm; altitude = 1 km; azimuthal angle = 0° (in the plane of the sun); surface albedo for green vegetation.



DEPENDENCE OF TOTAL RADIANCE FROM DIFFUSE SURFACE ON VISUAL RANGE AND SCAN ANGLE. Wavelength = 0.55 μm; solar zenith angle = 30°; azimuthal angle = 0° (in the plane of the sun); altitude = 1 km; surface albedo for green vegetation.

Figure 3.6.15. Dependence of Path Radiance on Visual Range and Scan Angle; Dependence of Total Radiance From Diffuse Surface on Visual Range and Scan Angle



TOTAL VERSUS PATH RADIANCE
(Total radiance vs. path radiance in the solar plane for various reflectances and optical thickness; Solar zenith angle = 45°, Wavelength = 0.55 μm, Nadir view angle = 0°)

Figure 3.6.16. Total Versus Path Radiance

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Before introducing any atmospheric correction algorithms, let us again consider the target radiance. In Figure 3.6.17 the surface element P is illuminated from the direction ϕ_0, θ_0 by direct solar radiance L_s as well as by the diffuse sky radiance L_D. The target radiance L_0 of this surface element will depend upon the radiance distribution of the incident light as well as the directional reflectance characteristics of the target. The target radiance is calculated by the first equation in Figure 3.6.18, where the first term is the radiance due to the reflectance of solar radiation and the second term is the target radiance due to reflection caused by the diffuse component. In this equation E_0 is the solar irradiance, $\mu_0 = \cos\theta_0$ is the solar zenith angle, τ_0 is the atmospheric optical thickness and p is the directional reflectance of the target. One may also define the intrinsic radiance of a target, which is the radiance to the reflectance by the target of a well collimated incident beam of light (Figure 3.6.18).

The target radiance is the quantity of interest. The radiance measured at the satellite must be corrected for path radiance and signal attenuation. The atmospheric correction algorithm for target radiance is given in Figure 3.6.19. As before T is the atmospheric transmittance. The atmospheric correction for instrinsic radiance differs from that for target radiance and is presented in Figure 3.6.20. Here $E_T(\tau_0)$ is the total or global irradiance at the earth's surface.

Most of the quantities needed for the atmospheric correction can be measured either directly or indirectly with varying degrees of difficulty. Often, however, the measurements are unavailable and these quantities must be calculated (Figure 3.6.21). Figure 3.6.22 illustrates the systems needed for the measurement of the atmospheric radiometric quantities. The optical thickness of the atmosphere may be determined by two methods:

(1) The diffuse target method, which uses two measurements of different <u>diffuse</u> targets from the spacecraft (Figure 3.6.23). If observations of two such targets have been made for several observation angles a graph such as that presented in Figure 3.6.24 may be drawn. The slope of the line is equal to the atmospheric optical depth.

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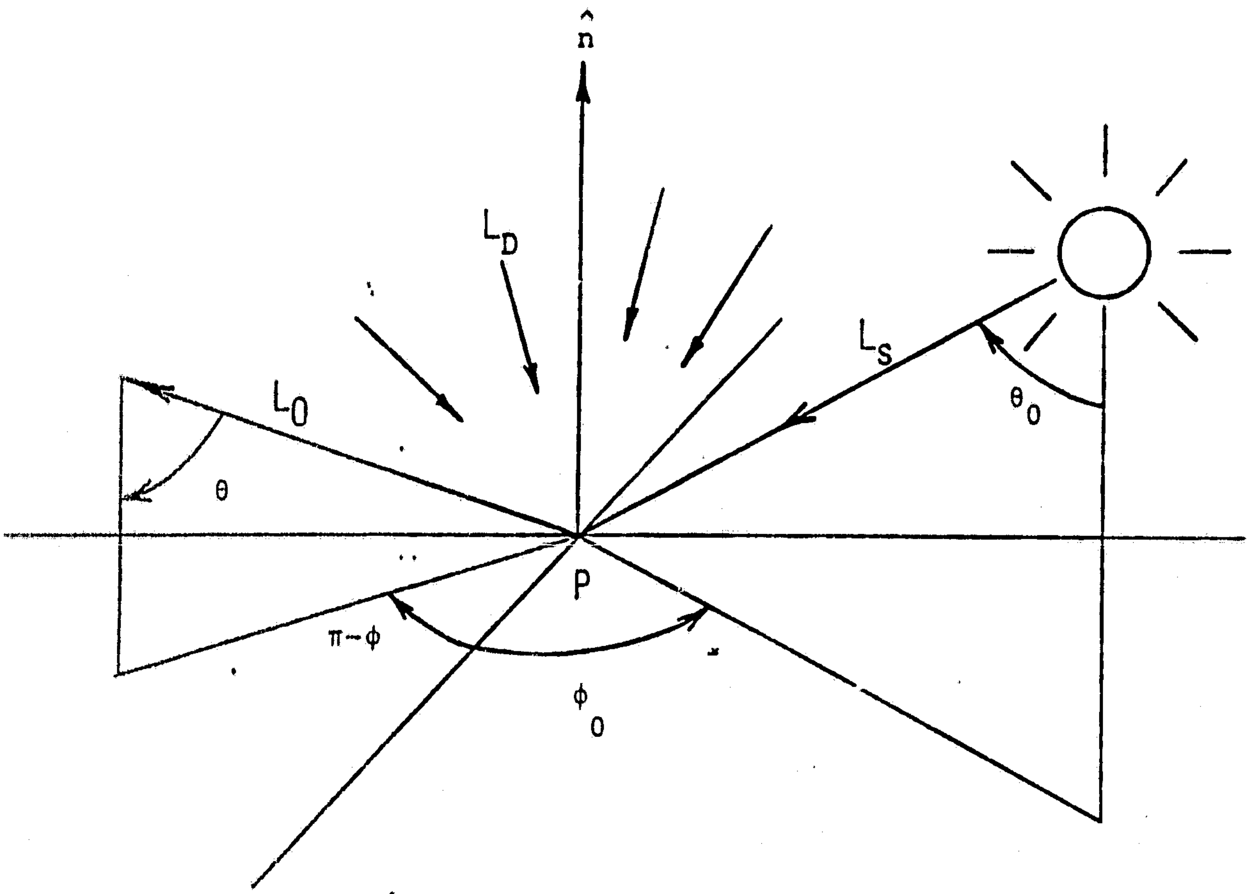

L_S SOLAR (DIRECT) RADIATION

L_D DIFFUSE SKY RADIATION

L_0 UPWARD RADIATION AT SURFACE

P SURFACE ELEMENT WITH BI-DIRECTIONAL REFLECTANCE

$\hat{n}$ NORMAL TO SURFACE ELEMENT

Figure 3.6.17. Radiation

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TARGET RADIANCE

$$L_0(\tau_0,\mu,\varphi) = \mu_0 E_0 e^{-\tau_0/\mu_0} \rho(\mu,\varphi,\mu_0,\varphi_0)$$

$$+ \int_0^{2\pi}\int_0^1 \mu' \rho(\mu,\varphi,\mu',\varphi') L_D(\tau_0,-\mu',\varphi') d\mu' d\varphi'$$

INTRINSIC RADIANCE

$$L_I(\mu,\varphi) = \mu_0 E_0 \rho(\mu,\varphi,\mu_0,\varphi_0)$$

Figure 3.6.18. Target Radiance; Intrinsic Radiance

ATMOSPHERIC CORRECTION ALGORITHM FOR SURFACE RADIANCE

$$L_o(\tau_o,\mu,\varphi) = F_o(\tau_o,\mu,\varphi)\, L(0,\mu,\varphi)$$

$$- G_o(\tau_o,\mu,\varphi)$$

$L(0,\mu,\varphi)$ ~ MEASURED BY SPACECRAFT SENSOR

$$F_o(\tau_o,\mu,\varphi) = \frac{1}{T(0,\mu)}$$

~ MEASURED BY SURFACE INSTRUMENTS

$$G_o(\tau_o,\mu,\varphi) = \frac{L_p(\tau_o,\mu,\varphi)}{T(0,\mu)}$$

~ CALCULATED BY RADIATIVE-TRANSFER MODELS

Figure 3.6.19. Atmospheric Correction Algorithm for Surface Radiance

ATMOSPHERIC CORRECTION ALGORITHM FOR INTRINSIC RADIANCE

$$L_I(\mu,\varphi) = F(\tau_0,\mu,\varphi)\, L(\tau_0,\mu,\varphi) - G(\tau_0,\mu,\varphi)$$

$L(\tau_0,\mu,\varphi) \sim$ MEASURED BY SPACECRAFT SENSOR

$$F(\tau_0,\mu,\varphi) = \frac{\mu_0 E_0}{E_T(\tau_0)\; T(0,\mu)}$$

$\sim$ MEASURED BY SURFACE INSTRUMENTS

$$G(\tau_0,\mu,\varphi) = F(\tau_0,\mu,\varphi)\, L_p(0,\mu,\varphi)$$

$\sim$ CALCULATED BY RADIATIVE-TRANSFER MODELS

Figure 3.6.20. Atmospheric Correction Algorithm for Intrinsic Radiance

DETERMINATION OF
REMOTE SENSING QUANTITIES (SPACE)

$L(0,\mu,\varphi)$ - MEASURED

$L_0(\tau_0,\mu,\varphi)$ - MEASURED; CALCULATED

$T(0,\mu)$ - MEASURED INDIRECTLY; I.E.,

$$T(0,\mu) = \left(\frac{E_s}{E_o}\right)^{\frac{\mu_o}{\mu}}.$$

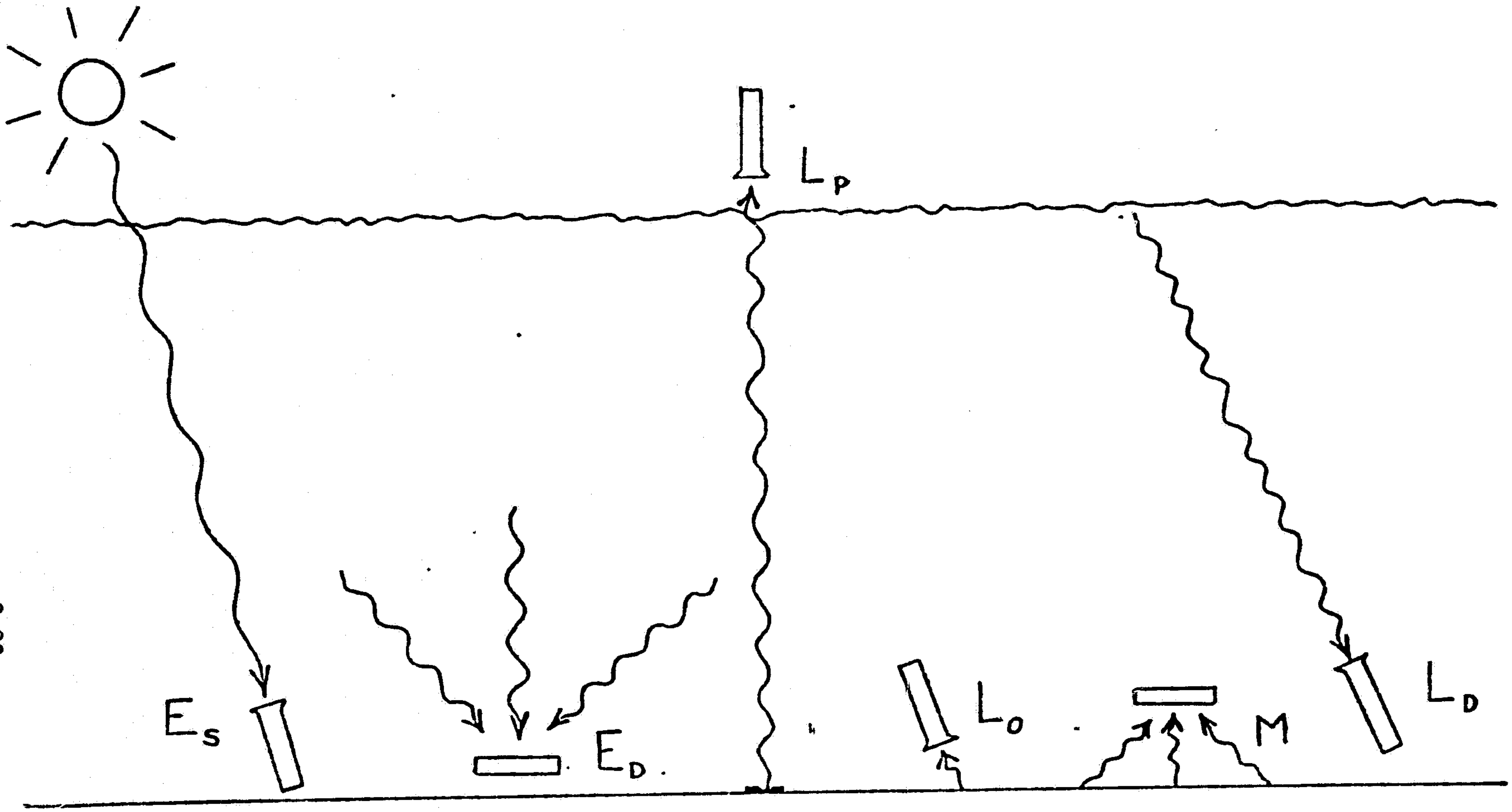
E_S - SOLAR IRRADIANCE AT TARGET

E_0 - EXTRATERRESTRIAL SOLAR IRRADIANCE

$L_p(0,\mu,\varphi)$ - MEASURED (DIFFICULT); CALCULATED

$L_D(\tau_0,-\mu,\varphi)$ - MEASURED; CALCULATED

Figure 3.6.21. Determination of Remote Sensing Quantities (Space)



SYSTEMS FOR THE MEASUREMENT OF ATMOSPHERIC RADIOMETRIC QUANTITIES IN REMOTE SENSING

Figure 3.6.22. Systems for the Measurement of Atmospheric Radiometric Quantities in Remote Sensing

OPTICAL THICKNESS DETERMINATION
(DIFFUSE TARGET METHOD)

$$L_1(\theta) = L_{01}T(\theta) + L_p(\theta)$$

$$L_2(\theta) = L_{02}T(\theta) + L_p(\theta)$$

$$D(\theta) \equiv L_1(\theta) - L_2(\theta)$$

$$= (L_{01} - L_{02})\, e^{-\tau_0 \sec\theta}$$

Figure 3.6.23. Optical Thickness Determination

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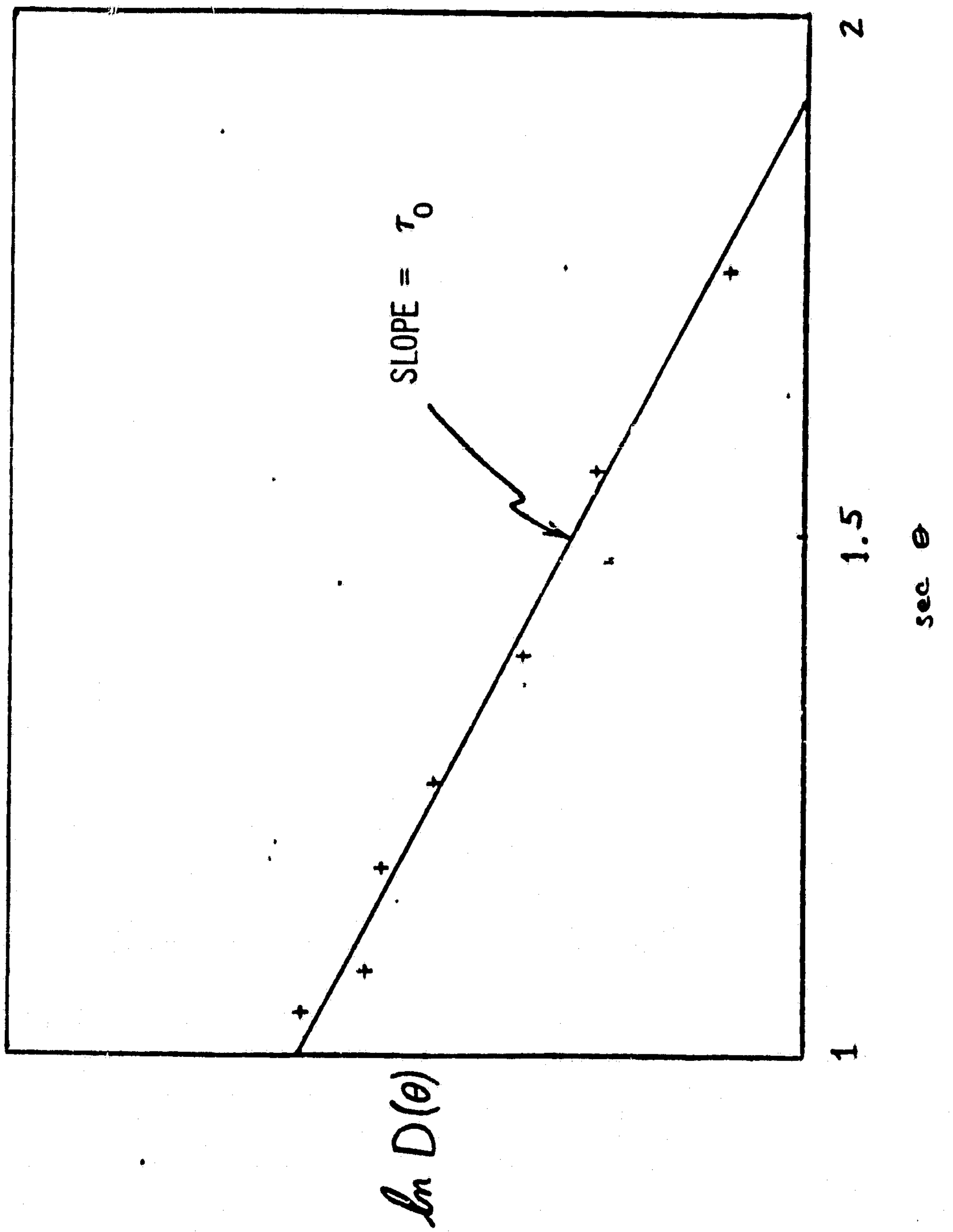

Figure 3.6.24.

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(2) Variation of parameters method, shown in Figure 3.6.25. The atmospheric correction is shown graphically in Figure 3.6.26.

There are many models which can be used to find the atmospheric correction. Many of these depend on meteorological parameters. The relationship between these meteorological parameters and the radiometric parameters are shown in Figure 3.6.27.

The MRS will allow us to investigate several problems associated with the atmospheric correction (Figure 3.6.28):

- Determine errors in the assumption of atmospheric homogeneity
- Determine the sensitivity of spacecraft radiance to variation in atmospheric parameters
- Examine the effects of non-diffuse targets.

OPTICAL THICKNESS DETERMINATION

(VARIATION OF PARAMETERS METHOD)

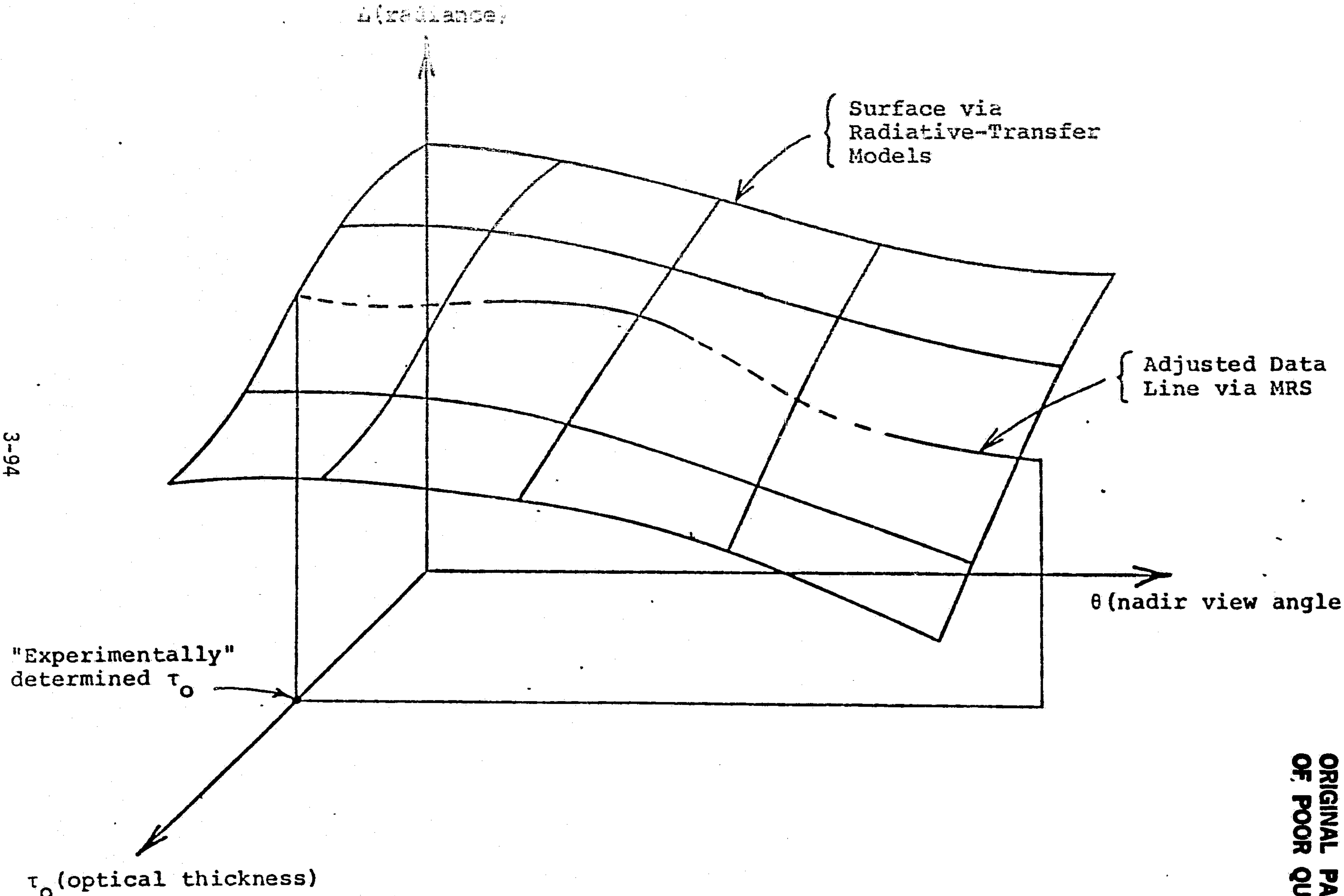
MINIMIZE THE FUNCTION

$$\left[L_{EXP}(\theta) - L_{MODEL}(\tau_0, \omega_0, \psi(r), \rho, \bar{\rho}) \right]^2$$

WITH RESPECT TO THE FIVE UNKNOWN PARAMETERS

τ_0 IS THEN DETERMINED

Figure 3.6.25. Optical Thickness Determination



TWO DIMENSIONAL SUBSPACE FOR ATMOSPHERIC CORRECTION

Figure 3.6.26. Two Dimensional Subspace for Atmospheric Correction

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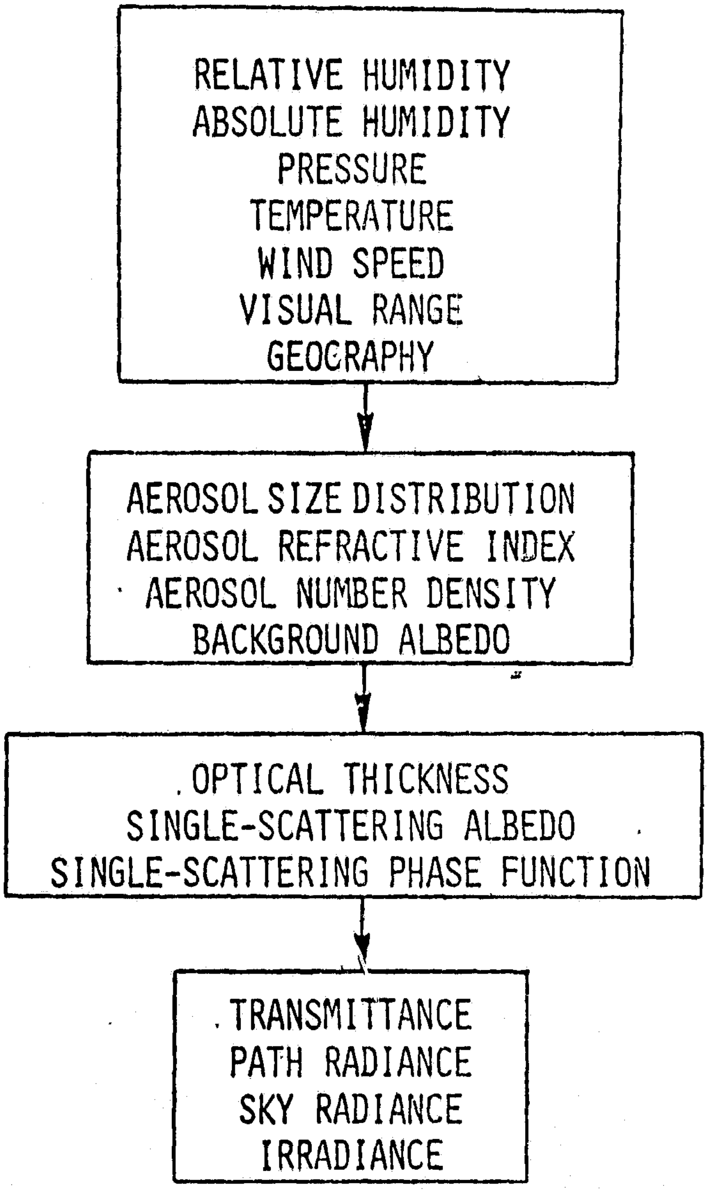

CONNECTION BETWEEN METEOROLOGICAL
PARAMETERS AND RADIOMETRIC PARAMETERS

Figure 3.6.27. Connection Between Meteorological Parameters and Radiometric Parameters

PROBLEMS TO BE INVESTIGATED

- DETERMINE ERRORS IN ASSUMPTION OF ATMOSPHERIC HOMOGENEITY
- DETERMINE SENSITIVITY OF SPACECRAFT RADIANCE TO VARIATION IN ATMOSPHERIC PARAMETERS
- EXAMINE EFFECTS OF NON-DIFFUSE TARGETS

Figure 3.6.28. Problems to be Investigated

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3.7 SPECTRAL SIGNATURES IN THE 0.4 TO 1.1μm REGION

GRAHAM R. HUNT

In remote sensing situations, information concerning the composition and nature of the Earth's surface is contained in the electromagnetic radiation reflected or emitted from the surface. The information is present in the form of intensity variations as a function of wavelength.

This presentation concerns the basic physical causes of these intensity variations for geological materials, especially in the 0.4 to 1.1μm range.

Figure 3.7.1 shows the EM spectrum from 0.25 to 30μm. The regions available for remote sensing are limited by the available atmospheric windows. Out to about 3 μm available energy is reflected, and from 3 μm to longer wavelengths, it is emitted.

For solids, compositionally diagnostic information is available because of the absorption or emission of specific amounts of energy which correspond to changes between the discrete, limited number of energy states in which a material can exist. For solids, these are discrete electronic or vibrational energy levels or electronic energy bands.

In the mid-infrared, the vibrational processes correspond to the fundamental stretching and bending modes, and relate directly to bulk composition. In the near IR they correspond to overtones and combinations of these fundamentals. In the visible, the features are due to electronic processes. In considering the 0.4 to 1.1 μm range, one is considering the spectral distribution of reflected skylight and sunlight, with any compositional informational due to variations in the electronic states of the material.

Information derived from reflected radiation pertains to the surface phenomena, because the incident radiation only penetrates from a few angstroms to a couple of millimeters. It is, therefore, primarily the materials' surface characteristics that affect the intensity of reflected radiation.

The important geological question is how the properties of this surface skin relate to the geology of the underlying structure.

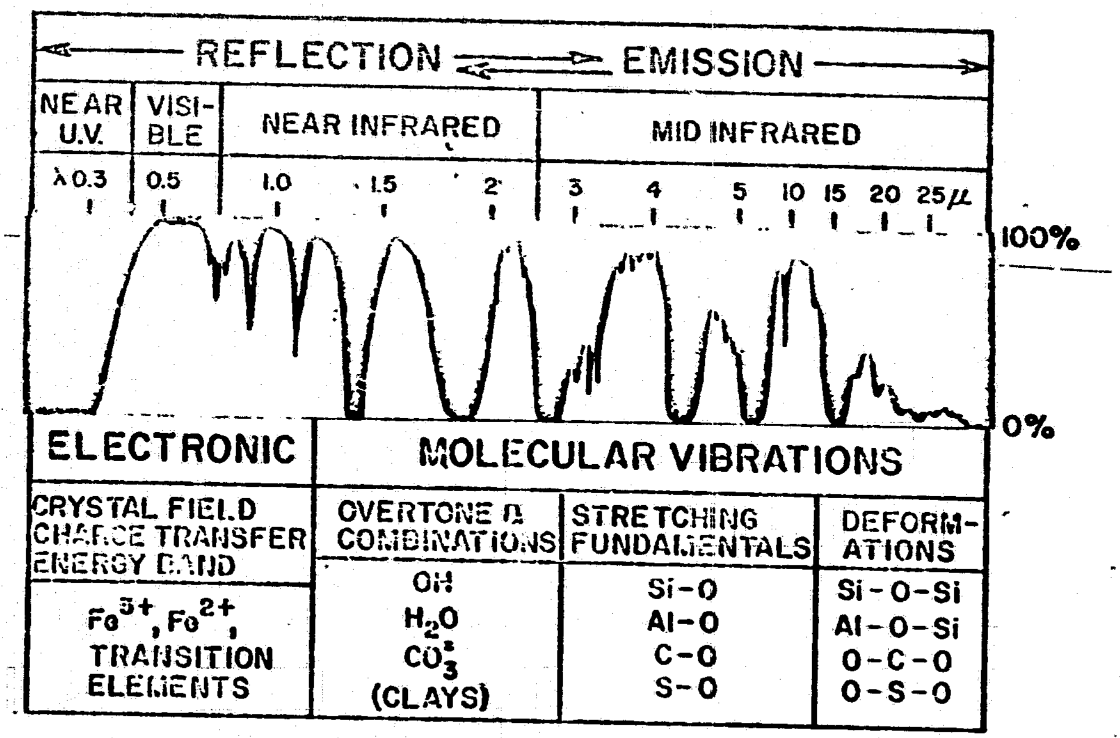

Figure 3.7.1 Reflection; Emission

The appearance and form of a reflection spectrum are governed by two types of effects, external and internal, shown in Figure 3.7.2. We will be concerned here primarily with internal effects.

In the 0.4 to 1.1 μm range, only a few oxides and sulphides absorb strongly enough to be considered significant. Few geologic materials, such as silicates, carbonates, sulphates and halides, etc., also absorb in this range unless they contain transition or rare earth element ions, either constitutionally or as impurities. The information available is a direct consequence of electronic processes, of which three are particularly important. They will be discussed separately.

Figure 3.7.3 lists these processes, which are so different that each requires a different theory to explain the process. These processes will be considered separately. From a practical standpoint, the most important thing about these different electronic processes is the intensity with which they occur.

3.7.1 Charge Transfer

The absorption of energy causes an electron to be transferred between adjacent ions, usually oxygen and a metal ion. The band produced is extremely intense, 10^4 to 10^6 times stronger than crystal field bands. Typically these bands occur in the far U.V. But for Fe^{3+}-O, it occurs in the near U.V. and is so intense its tail extends into the visible. How far it extends depends on the Fe^{3+}-O concentration. It is this band which dominates the spectra of geologic materials, accounting for the yellow, beige, tan, brown and red color of most rocks and soils. There are other charge transfer bands, such as Fe^{3+}-Fe^{2+} in augite, but they are weak by comparison, generally because of low mineralogic concentrations.

Figure 3.7.4 shows charge transfer features in goethite (Fe^{3+}-O), augite (Fe^{3+}-Fe^{2+}), and carnotite (U-O). Areas corresponding to location and halfwidth of the bands produced are indicated, and these areas will be transferred to the summary diagram.

<u>1. EXTERNAL EFFECTS</u>

<u>a) NATURE OF THE SURFACE</u>
smooth, rough, particulate

<u>b) PHYSICAL ENVIRONMENT</u>
topography, pressure, temperature

<u>2. INTERNAL EFFECTS</u>

<u>a) COMPOSITION</u>
chemistry, number and kinds of atoms
geometry--structure
single or multiple components

Figure 3.7.2 External and Internal Effects

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ELECTRONIC PROCESSES

1. CHARGE TRANSFER
Molecular Orbital Theory
Extremely Intense

2. CRYSTAL FIELD TRANSITIONS
Crystal Field Theory
Forbidden, Very weak

3. TRANSITIONS TO CONDUCTION BAND
Electron Band Theory
Intense

Figure 3.7.3 Electronic Processes

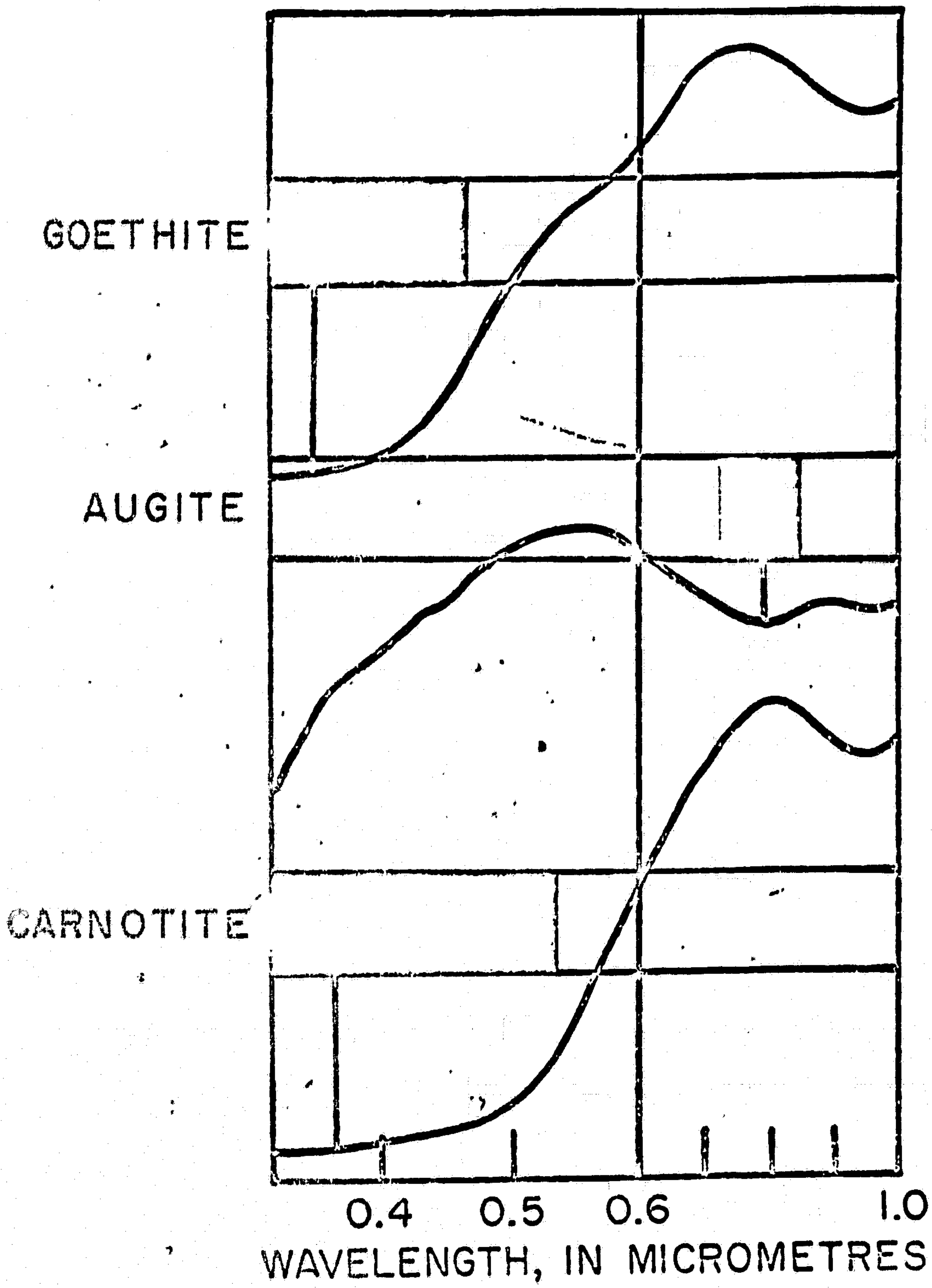

Figure 3.7.4 Wavelength, in Micrometres

3.7.2 Crystal Field Transition (CFT) Bands

These crystal field bands are caused by transitions between energy levels of an ion which have been perturbed--split and displaced--by interaction with the crystal field in which it is located. The same ion located in different fields will yield different spectra, providing indirect information about the crystal structure. Ions that produce bands in the visible and NIR are the transition elements (d electrons) and rare earth elements (f electrons). The most commonly occurring ion in geologic matérials is Fe^{3+}, but its CFT bands, being forbidden, are weak, and the shorter wavelength ones are typically swamped by the intense charge transfer band. There are some Fe^{3+} containing minerals that show the CFT bands due to a process called intensity stealing.

Figure 3.7.5 shows six spectra of a sample of rhodochrosite in which the bands are due to crystal field transitions in Mn^{2+}. Rhodochrosite was chosen as an illustration because the Mn^{2+} ion is isoelectronic with the ferric ion, so the arrangement of its bands are the same as for Fe^{3+} but their locations are different. The spectra are for the same sample of rhodochrosite prepared in six different ways--from less than 5 μ-sized particles to a polished plate. The effect of particle size is to increase the overall reflection as the particle size decreases, but to decrease the contrast of the bands. However, no matter what the condition of the material, the location and relative intensities of the bands remain constant. These spectra show some of the sharpest, best resolved features observed in mineral spectra.

Figure 3.7.6 shows the effect of decreasing the spectral resolution--how using insufficient resolution results in the loss of detail and eventual loss of bands altogether.

Figure 3.7.7 shows the crystal field bands found in minerals containing (from the top) nickel, cupric, ferric, maganic, chromic, and lanthanum ions, and these bands will be observed in essentially this form in the spectra of any mineral containing these ions.

Figure 3.7.8 illustrates how a crystal field spectrum for a particular ion may vary depending on the crystal field in which it is located. In the minerals shown, all the bands are due to the presence of ferrous ions (Fe^{2+}) located in different crystal fields, which are listed at the side in Figure 3.7.9.

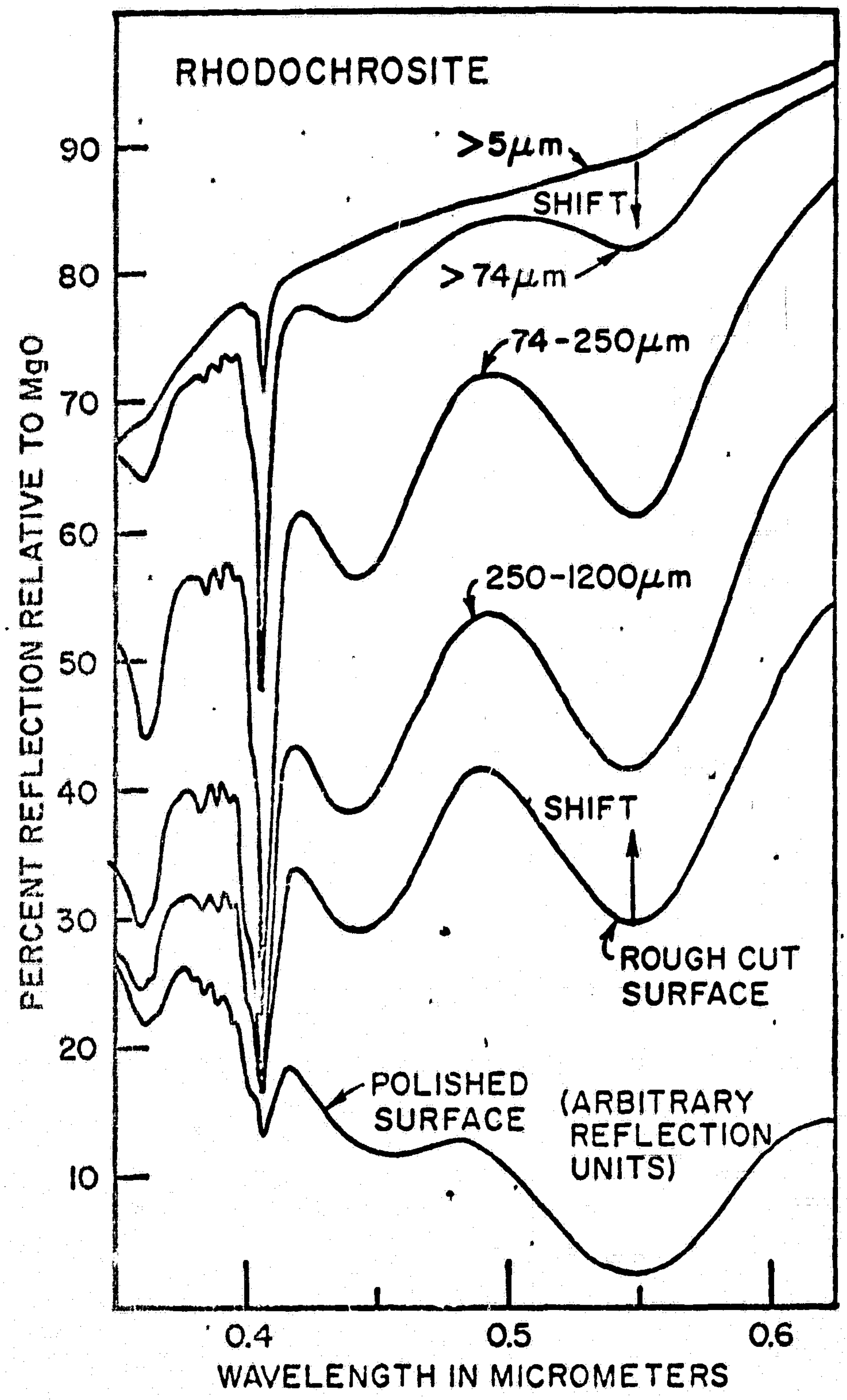
RHODOCHROSITE
>5μm
SHIFT
>74μm
74-250μm
250-1200μm
SHIFT
ROUGH CUT SURFACE
POLISHED SURFACE
(ARBITRARY REFLECTION UNITS)
PERCENT REFLECTION RELATIVE TO MgO
90
80
70
60
50
40
30
20
10
0.4
0.5
0.6
WAVELENGTH IN MICROMETERS

Figure 3.7.5

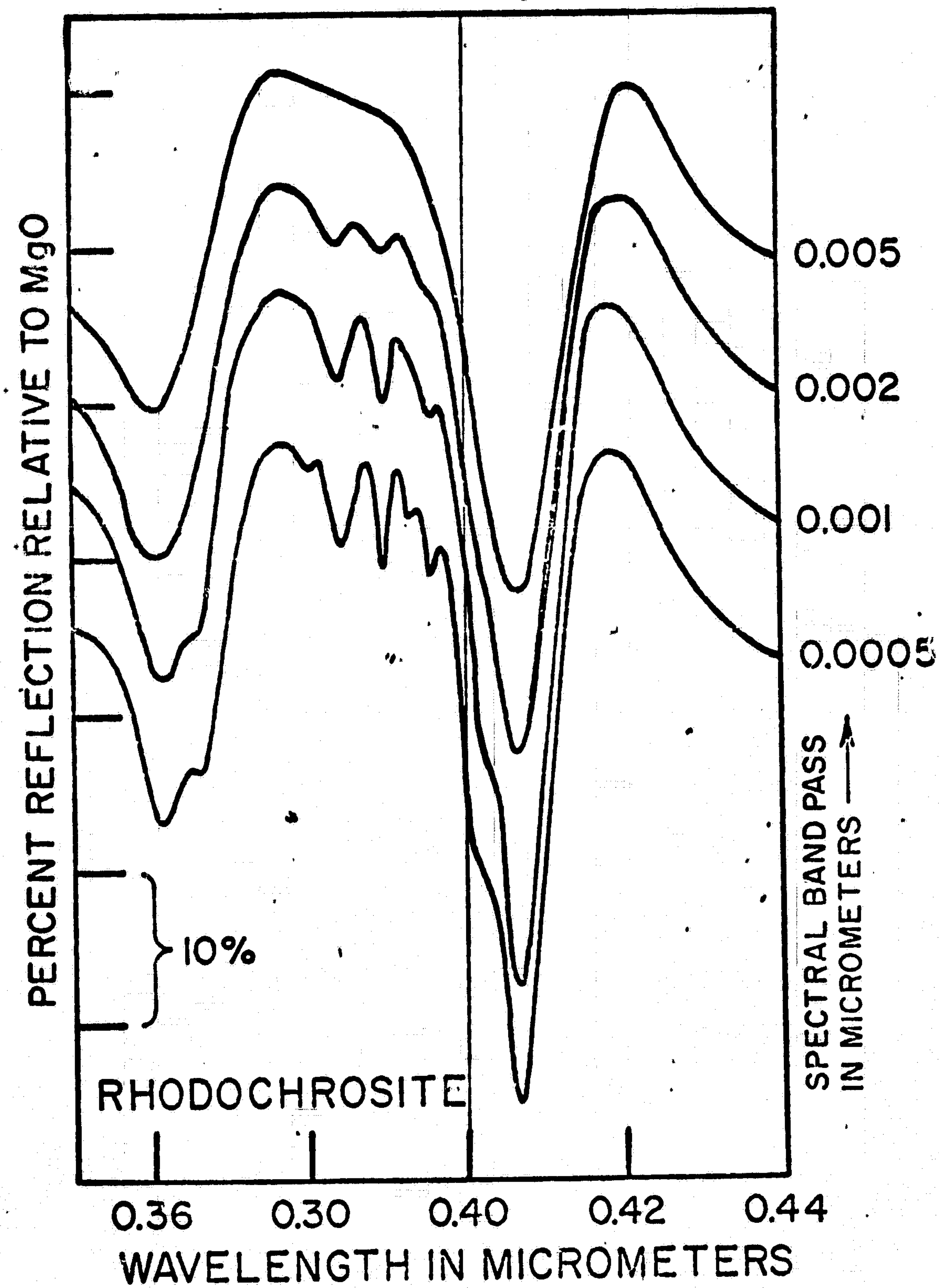

Figure 3.7.6

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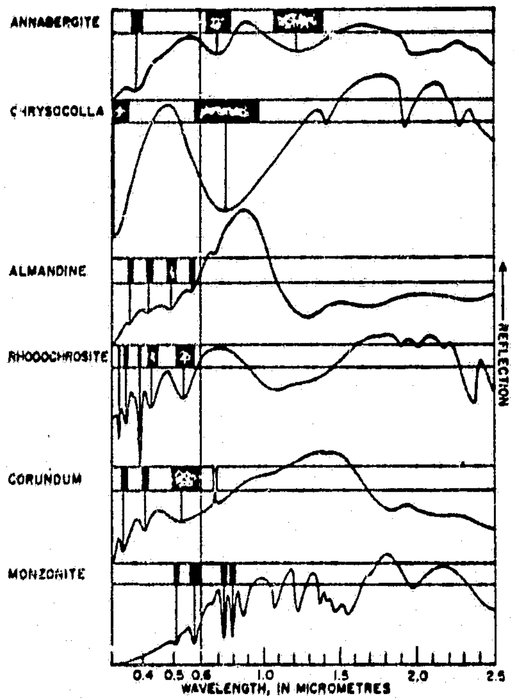
ANNABERGITE
CHRYSOCOLLA
ALMANDINE
RHODOCHROSITE
CORUNDUM
MONZONITE
REFLECTION
0.4 0.5 0.6 1.0 1.5 2.0 2.5
WAVELENGTH, IN MICROMETRES

Figure 3.7.7

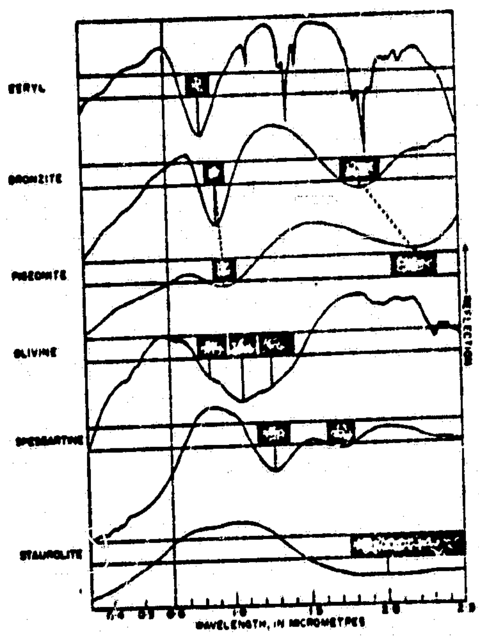
BERYL
BRONZITE
PIGEONITE
OLIVINE
SPESSARTINE
STAUROLITE
REFLECTANCE
WAVELENGTH, IN MICROMETRES

Figure 3.7.8

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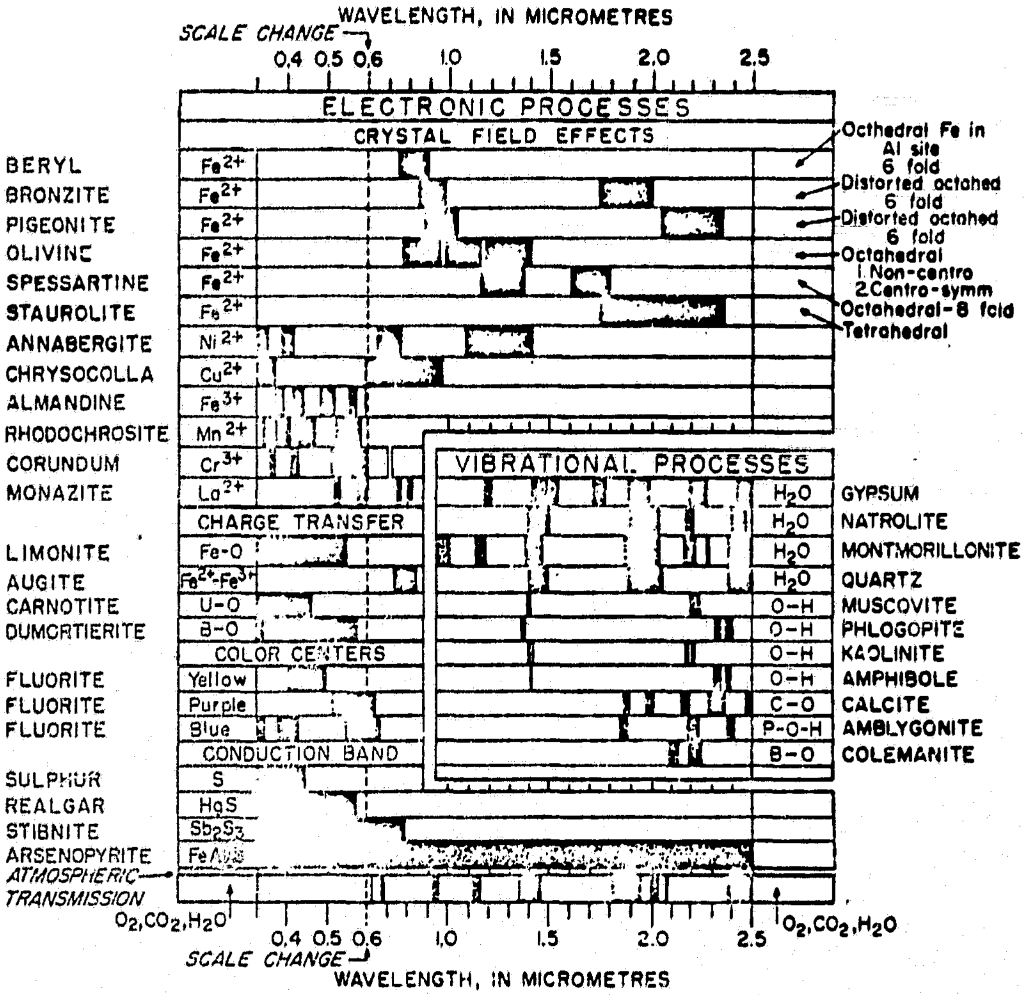

Figure 3.7.9

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3.7.3 Transitions to the Conduction Band

In some materials, there are energy bands rather than discrete energy levels. In these materials the conduction band is separated from the valence bands by an energy gap. The spectra of such materials are characterized by a region of complete transmission followed by a region of complete absorption with a very sharp absorption edge. This type of spectrum occurs most frequently for geological materials in sulfides, as illustrated in Figure 3.7.9.

The information discussed and shown in the previous figures is collected into a summary diagram (Figure 3.7.10) which collects together all the available information for minerals.

The most important thing to remember about these data is that the spectrum of a given material of a given particle size does not change. The data given so far refer to pure minerals. When minerals are mixed together to form rocks, the spectrum of the rock is a composite of the individual mineral spectra of which it is composed. For reflection spectra, a simple mixing law cannot be used because the contribution each constituent makes is a function of its accessibility to the interacting radiation.

Figure 3.7.11 shows the spectra of three minerals that dominate the spectra of hydrothermally altered rocks. The important features to notice in these spectra are the sharp band near 0.42μm in jarosite, the broad crystal field band in hematite near 0.85μm, and the two CFT bands near 0.65 and 0.93μm in geothite.

Figure 3.7.12 shows the spectra of hydrothermally altered rocks that contain between 2 and 15% jarosite. In all of them, the 0.42 feature is clearly evident.

Figure 3.7.13 shows spectra of rocks which contain hematite as a major component, or in greater concentrations than goethite if it is present. In these spectra, the minimum is to shorter wavelengths than 0.9μm.

Figure 3.7.14 shows spectra of rocks which contain goethite (or jarosite) as a major component, or in higher concentrations than hematite, if it is present. In these cases, the minimum of the CFT band is to longer wavelengths than 0.9μm, and in all of them the 0.65μm feature is clearly evident as a shoulder.

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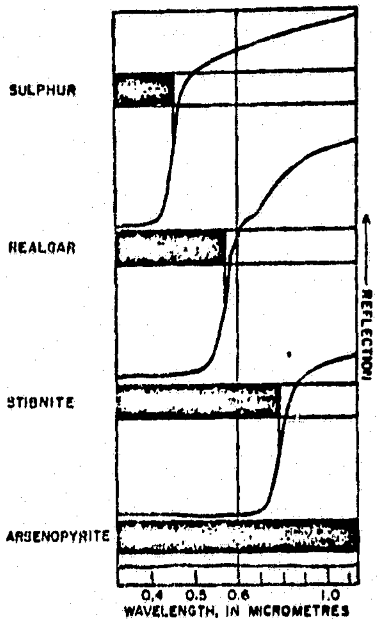

Figure 3.7.10

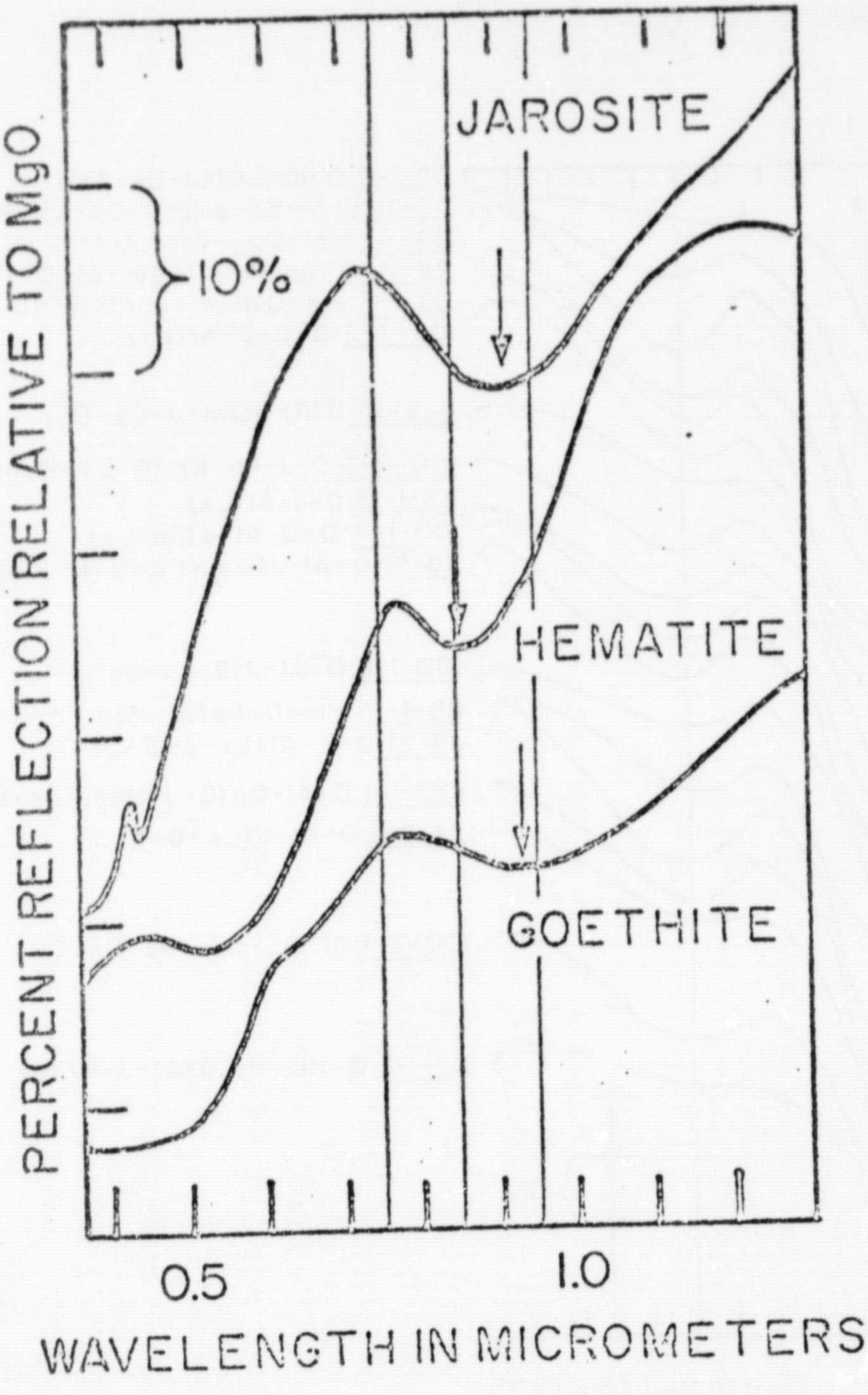

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Figure 3.7.11

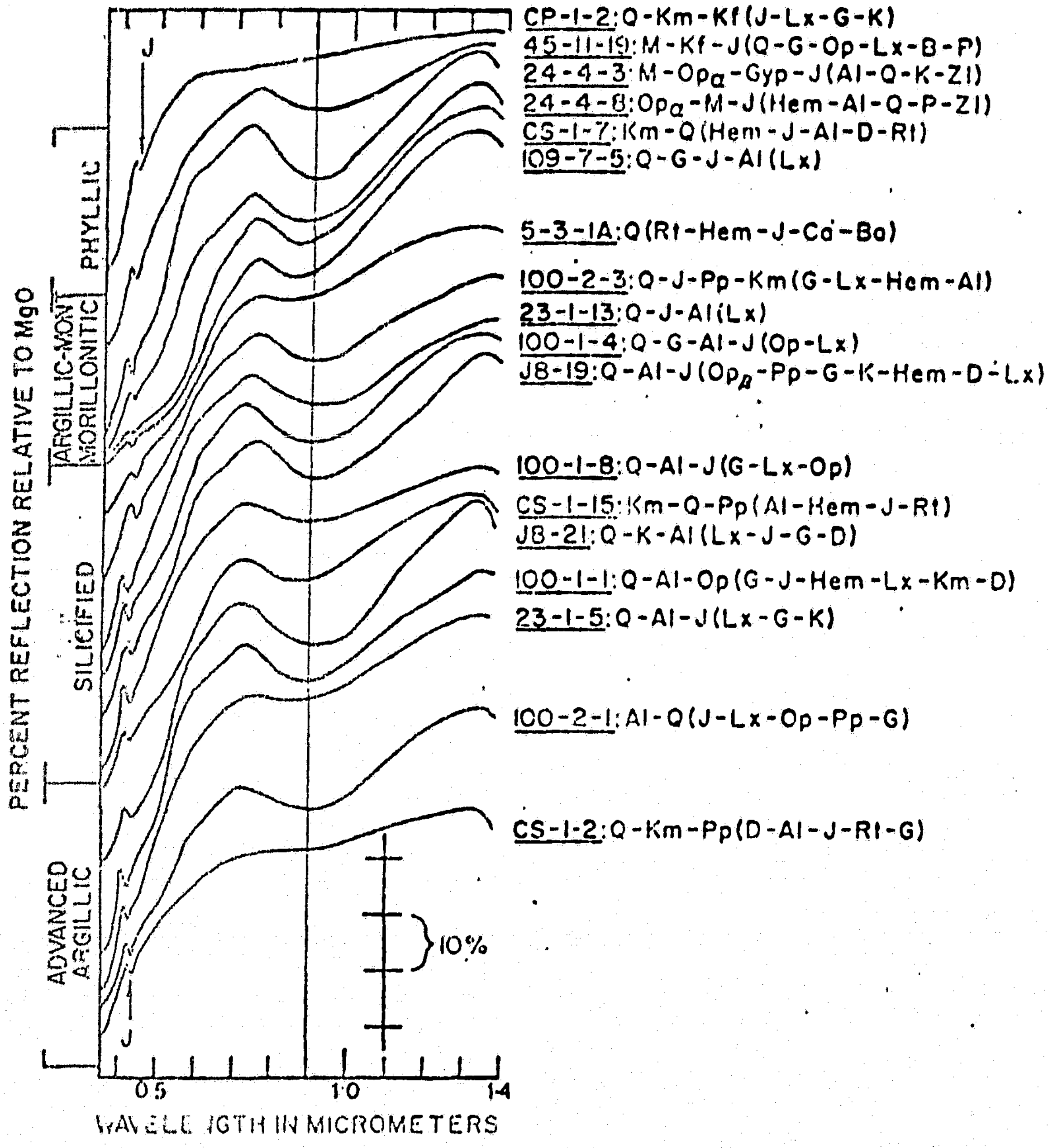
CP-1-2:Q-Km-Kf(J-Lx-G-K)
45-11-19:M-Kf-J(Q-G-Op-Lx-B-P)
24-4-3:M-Opα-Gyp-J(Al-Q-K-Zl)
24-4-8:Opα-M-J(Hem-Al-Q-P-Zl)
CS-1-7:Km-Q(Hem-J-Al-D-Rt)
109-7-5:Q-G-J-Al(Lx)
5-3-1A:Q(Rt-Hem-J-Ca-Ba)
100-2-3:Q-J-Pp-Km(G-Lx-Hem-Al)
23-1-13:Q-J-Al(Lx)
100-1-4:Q-G-Al-J(Op-Lx)
J8-19:Q-Al-J(Opβ-Pp-G-K-Hem-D-Lx)
100-1-8:Q-Al-J(G-Lx-Op)
CS-1-15:Km-Q-Pp(Al-Hem-J-Rt)
J8-21:Q-K-Al(Lx-J-G-D)
100-1-1:Q-Al-Op(G-J-Hem-Lx-Km-D)
23-1-5:Q-Al-J(Lx-G-K)
100-2-1:Al-Q(J-Lx-Op-Pp-G)
CS-1-2:Q-Km-Pp(D-Al-J-Rt-G)
J
J
PHYLLIC
ARGILLIC-MONT MORILLONITIC
SILICIFIED
ADVANCED ARGILLIC
PERCENT REFLECTION RELATIVE TO MgO
10%
0.5
1.0
1.4
WAVELENGTH IN MICROMETERS

Figure 3.7.12

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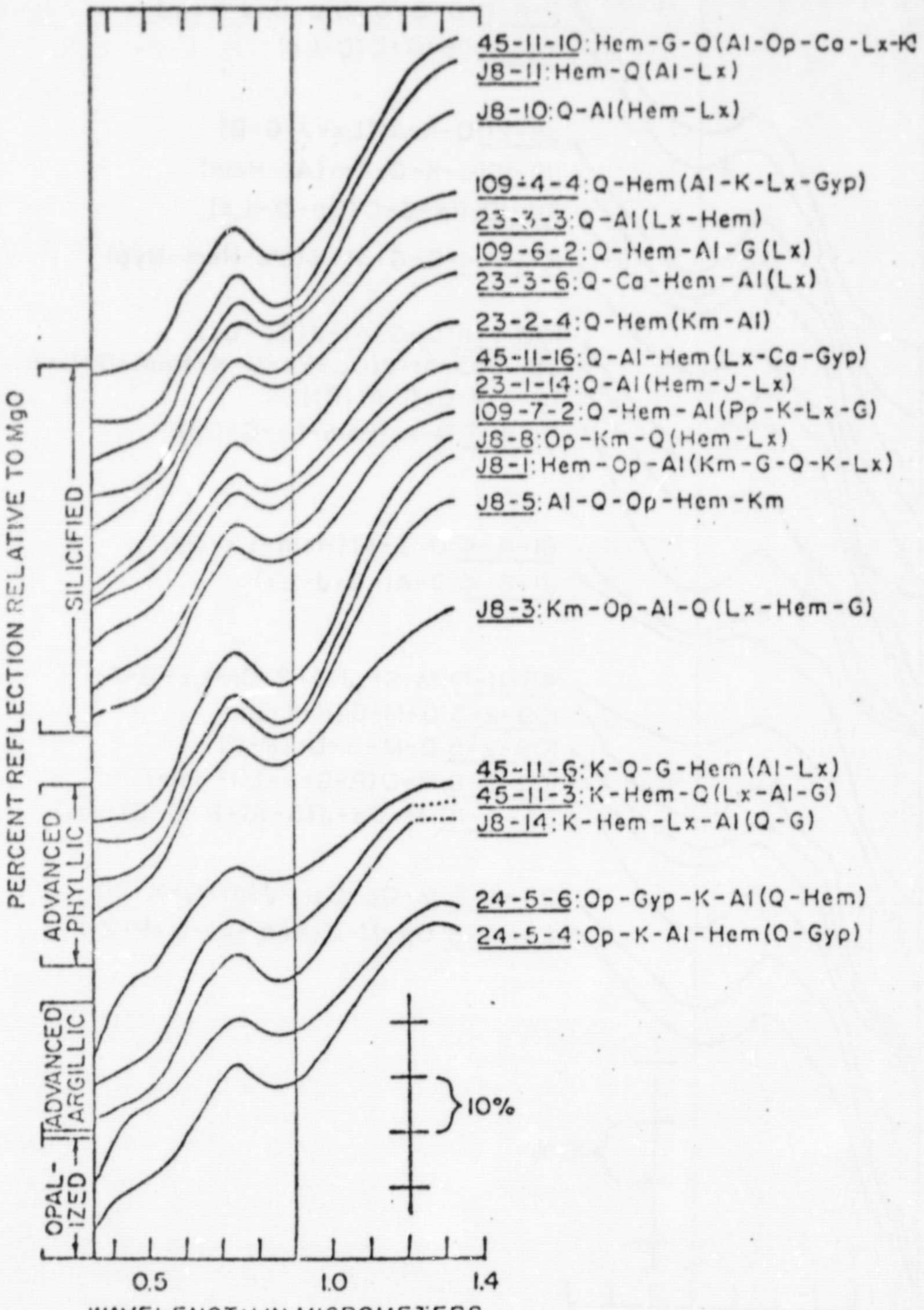

Figure 3.7.13

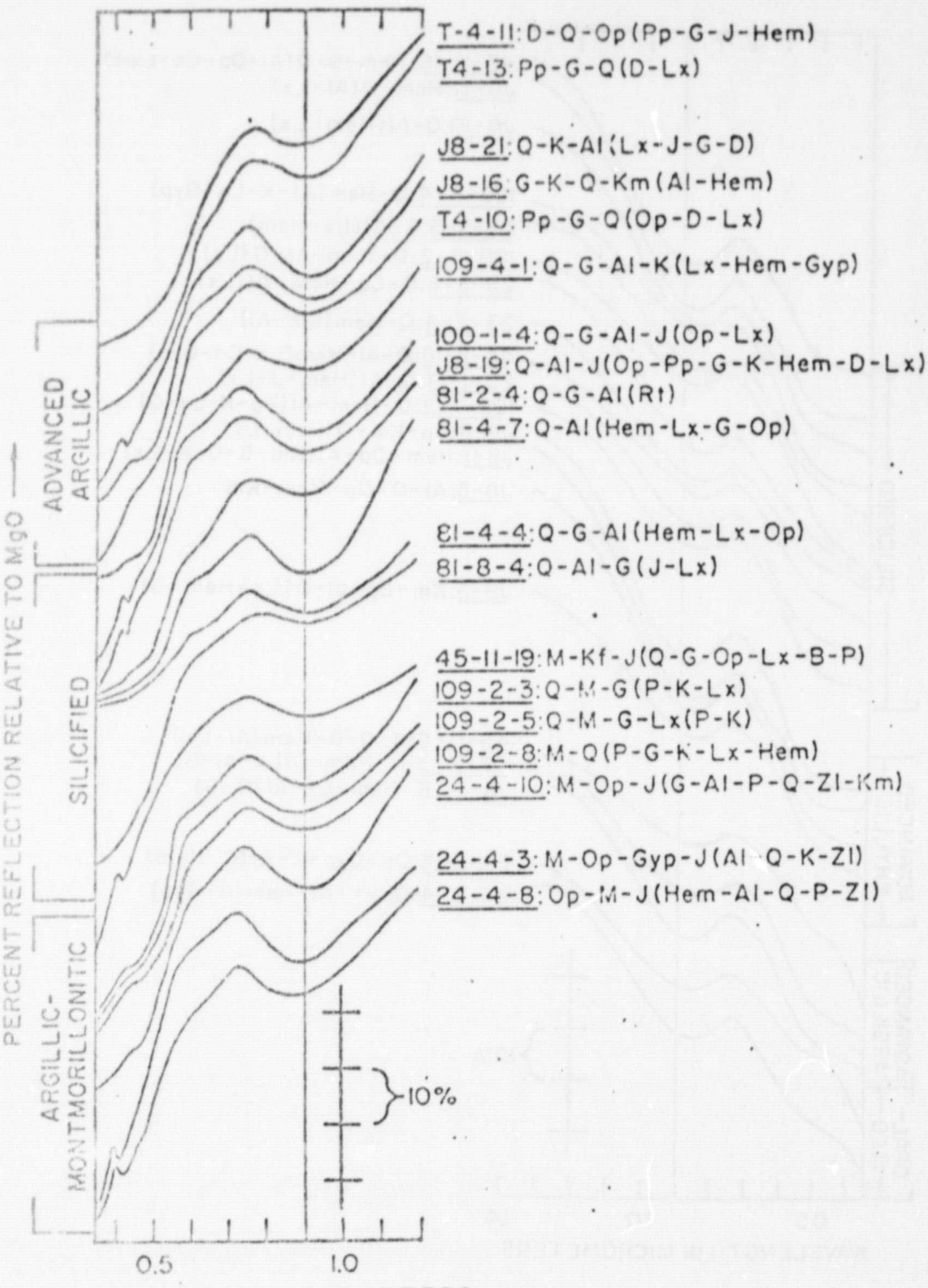
T-4-11: D-Q-Op(Pp-G-J-Hem)
T4-13: Pp-G-Q(D-Lx)
J8-21: Q-K-Al(Lx-J-G-D)
J8-16: G-K-Q-Km(Al-Hem)
T4-10: Pp-G-Q(Op-D-Lx)
109-4-1: Q-G-Al-K(Lx-Hem-Gyp)
100-1-4: Q-G-Al-J(Op-Lx)
J8-19: Q-Al-J(Op-Pp-G-K-Hem-D-Lx)
81-2-4: Q-G-Al(Rt)
81-4-7: Q-Al(Hem-Lx-G-Op)
81-4-4: Q-G-Al(Hem-Lx-Op)
81-8-4: Q-Al-G(J-Lx)
45-11-19: M-Kf-J(Q-G-Op-Lx-B-P)
109-2-3: Q-M-G(P-K-Lx)
109-2-5: Q-M-G-Lx(P-K)
109-2-8: M-Q(P-G-K-Lx-Hem)
24-4-10: M-Op-J(G-Al-P-Q-Zl-Km)
24-4-3: M-Op-Gyp-J(Al-Q-K-Zl)
24-4-8: Op-M-J(Hem-Al-Q-P-Zl)
ADVANCED ARGILLIC
SILICIFIED
ARGILLIC-MONTMORILLONITIC
PERCENT REFLECTION RELATIVE TO MgO
10%
0.5
1.0
WAVELENGTH IN MICROMETERS

Figure 3.7.14

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In Figure 3.7.15 generalizations are made about rock spectra, summarizing essentially what is available in a remote sensing situation.

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ROCK SPECTRAL GENERALIZATIONS

1. UNALTERED ROCKS
   a) FELSIC: Highest reflectivity, featureless.
   b) INTERMEDIATE: Lower reflectivity, featureless.
   c) MAFIC: Lowest reflectivity, CFT Fe^{2+} 1.0μm.
   d) ULTRAMAFIC: higher reflectivity than mafic,
      Intense CFT Fe^{2+} near 1.0μm.
   e) SEDIMENTARY } Transparent, show CFT
      METAMORPHIC } eg. Marbles-Mn^{2+}; Quartzites-Cr^{3+}

2. ALTERED ROCKS
   Spectra dominated by Fe^{3+} oxides & oxyhydroxides.
   Color largely a function of Fe^{3+} concentration.
   a) Charge-transfer Fe^{3+}-O dominates short λ.
   b) CFT of Fe^{3+} near 0.65 and 0.9μm.
   c) Sharp Fe^{3+} CFT near 0.42μm, intensity stealing.

3. SULPHIDES
   Sharp absorption edge, characteristic of metal.

Figure 3.7.15

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3.8 SPECTRAL FEATURES IN THE 0.4 TO 1.0 NM REGION FOR VEGETATION ANALYSIS

DR. STEPHEN UNGAR

The major feature of the spectral reflectance of vegetation are quite similar for most species. Figure 3.8.1 illustrates these features:

- Chlorophyll absorption in the 0.5 μm to 0.7 μm range
- Strong reflection in the infrared
- Absorption by water in the leaf at 1.4 μm and 1.9 μm.

The water absorption bands can be useful for vegetation analysis, particularly if reflectance measurements are made at the earth's surface. However, in most aircraft measurements, and certainly in satellite observations, atmospheric water vapor will also absorb light at these wavelengths seriously interfering with this measurement. The effect of atmospheric water vapor absorption can be seen in Figure 3.8.2 which shows the solar energy curve at sea level along with the solar energy curve outside the atmosphere. The other atmospheric absorption bands apparent in Figure 3.8.2 (see also Figure 3.8.3) do not have as great an impact on the vegetation reflectance curves.

Figures 3.8.4 and 3.8.5 show several reflectance curves for clean, tilled soil and for winter wheat respectively. These data were collected in Finney County, Kansas, on 21 May, 1975 with the Fast Scanning Spectrometer (FSS) The strong variation in reflectance occurring in both sets of curves at approximately 1.9 μm is not primarily due to differences in leaf water content. These variations are introduced by the low signal to noise ratio in this band due to strong atmospheric water vapor absorption. Reflectance is calculated from FSS measurements by ratioing observations to readings obtained over a standard reflectance plate. Thus, in the 1.9 μm band we are calculating a ratio of two very small numbers (because of low incident radiation) and variations of one or two instrument counts will produce large changes in calculated reflectance. This effect can also be seen in the 1.4 μm water absorption band although there, the effect is somewhat reduced. Thus, we may not lose very much information for vegetation analysis by restricting observations to wavelengths below 1.1 μm which is the limit of detection for the MRS sensor.

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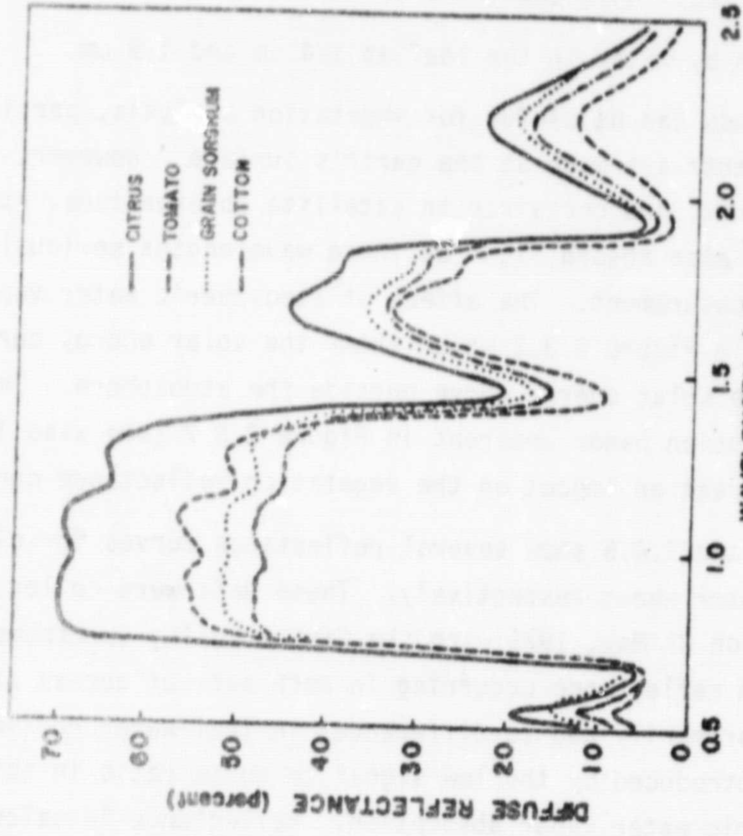

From Remote Sensing - With Special Reference to Agriculture and Forestry, National Academy of Sciences, 1970

Figure 3.8.1

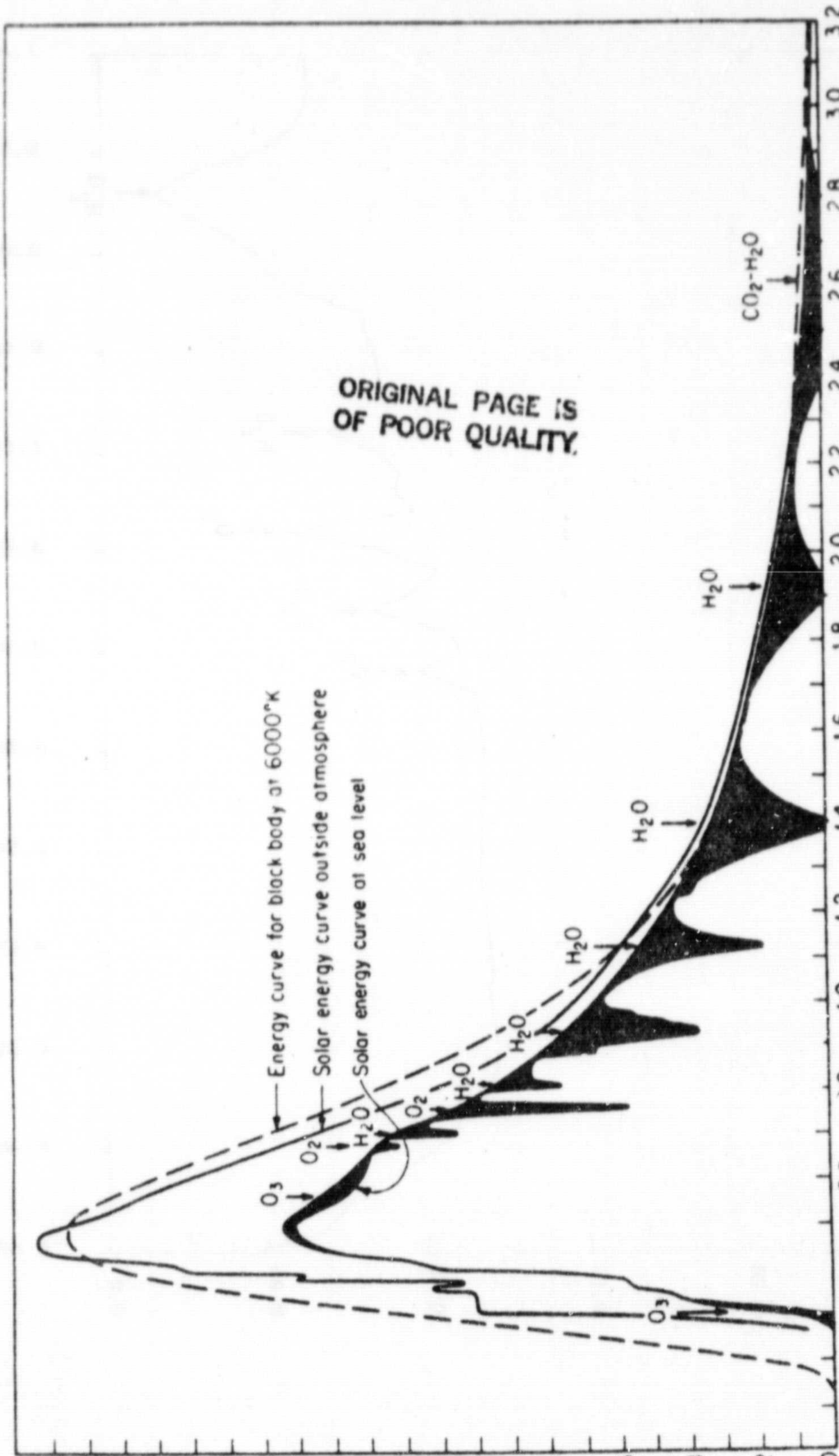

Figure 3.8.2. Atmospheric Water Vapor Absorption

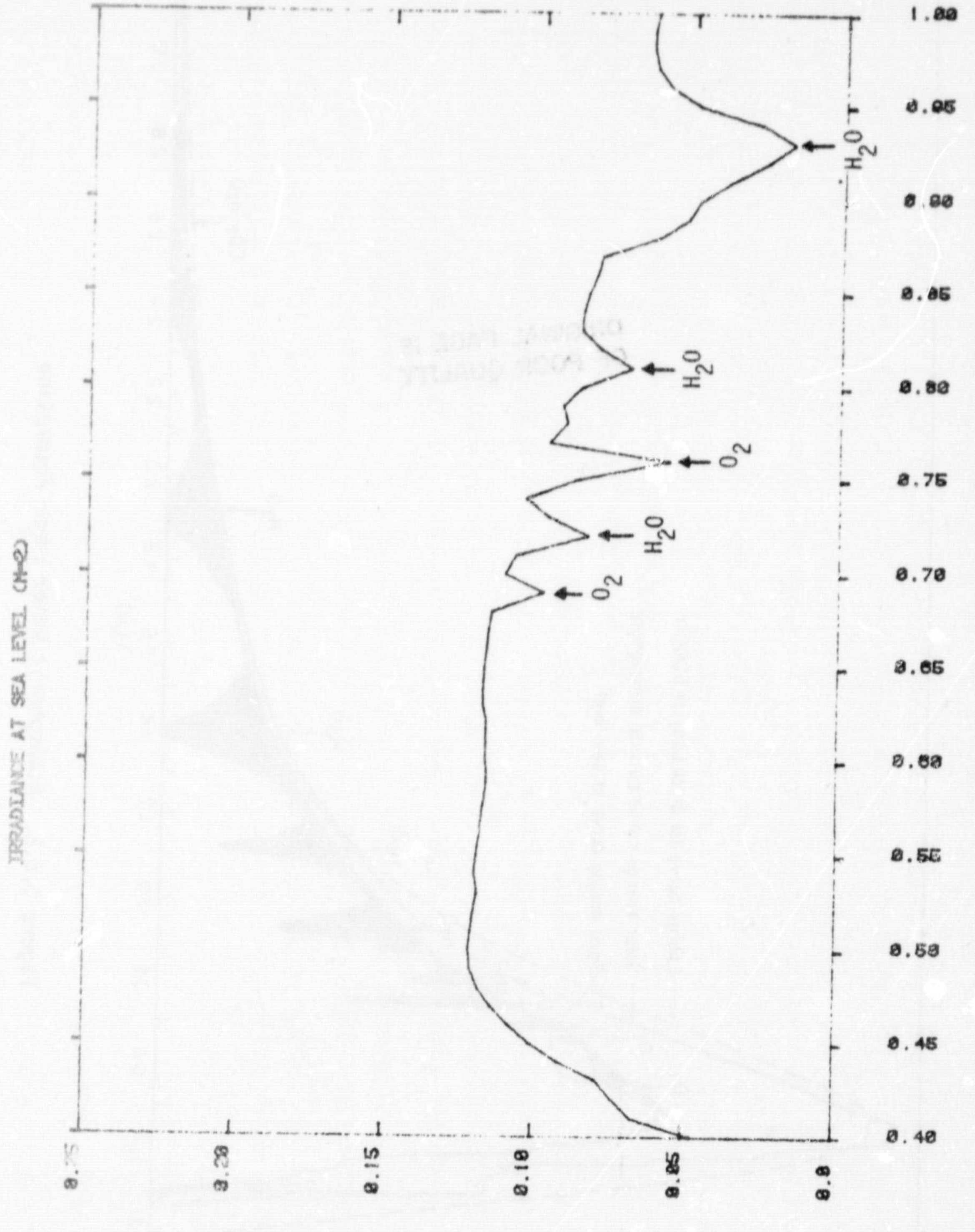

Figure 3.8.3. Atmospheric Absorption Bands

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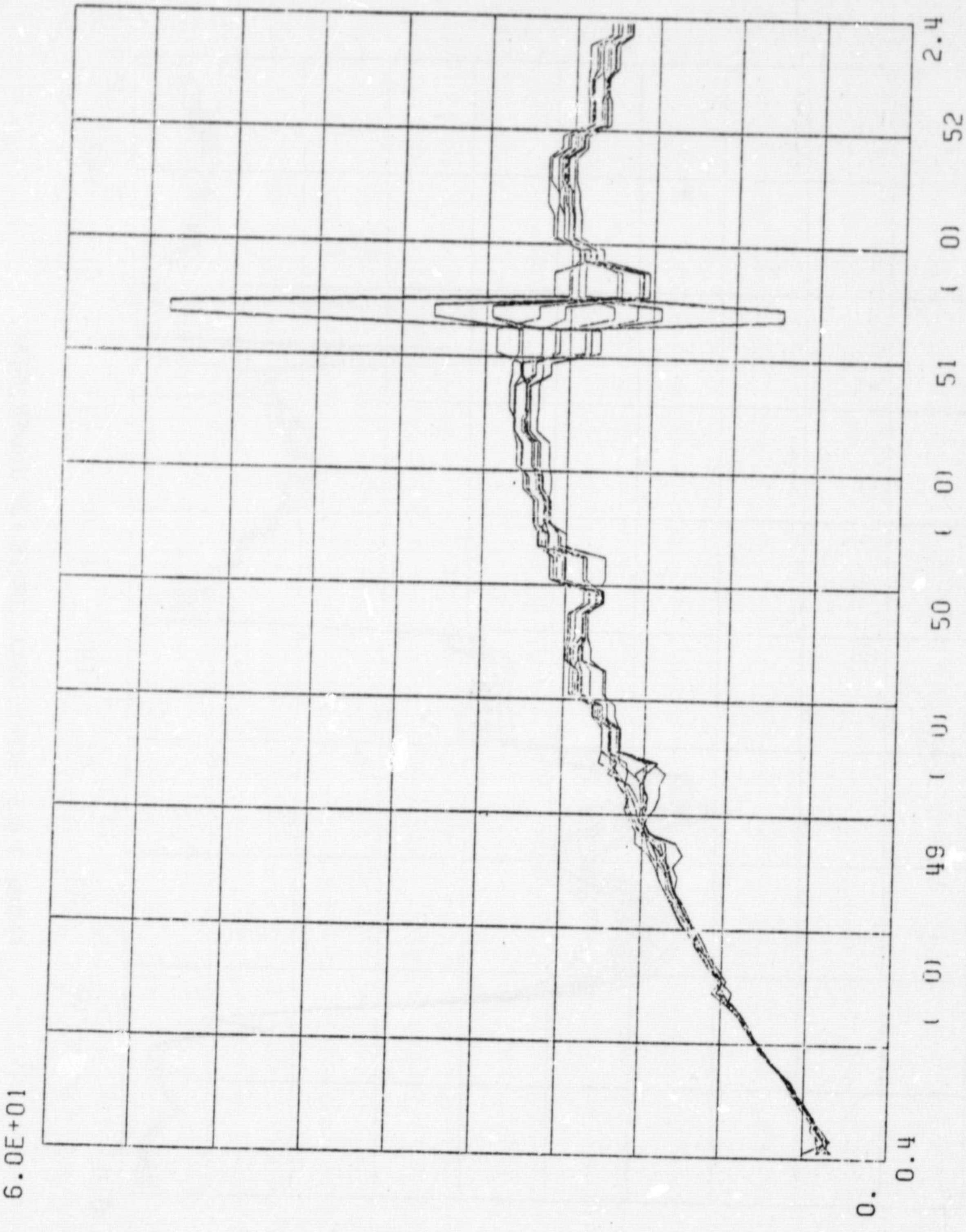

FIGURE 3.8.4 REFLECTANCE CURVES FOR CLEAN, TILLED SOIL, FINNEY CO., KANSAS 5/21/75

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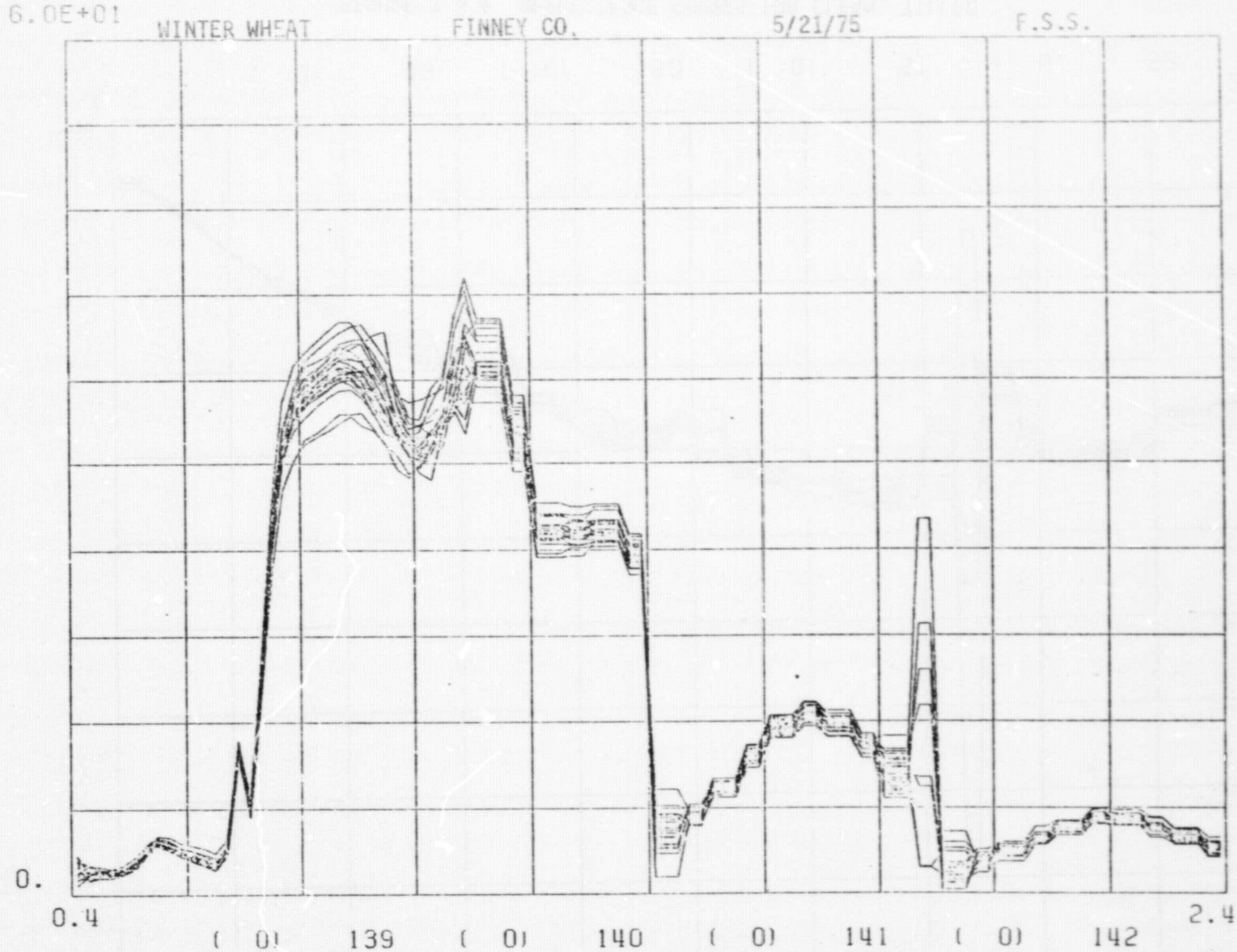

FIGURE 3.8.5 REFLECTANCE CURVES FOR WINTER WHEAT,
FINNEY CO., KANSAS 5/21/75

Figure 3.8.6 shows the reflectance curves for winter wheat in the 0.4 to 1.0 µm spectral region. These curves are fairly typical for reflectance from vegetation. Apparent in these curves is the absorption through the visible region and the strong reflectance in the infrared. There is a slight peak at approximately 0.55 µm (green) which divides the absorption region. This peak accounts for the green appearance of healthy vegetation. (The peak at 0.7 µm is an artifact of the scanner and is due to the change in filters.) The same reflectance characteristics are seen in reflectance curves for other species (Figure 3.8.7).

The most obvious feature of these curves is the step-function-like shift when moving from the strong absorption region in the visible to the high reflectance region in the infrared. We might call this the zero'th order approximation (Figure 3.8.8). Most vegetation indicators are based entirely on this approximation and use of ratio of infrared to red reflectance as a measure of vegetative cover.

Some indicators do take into account the local maximum of reflectance in the green, by using a ratio of green to red reflectance. Inclusion of the green peak in approximating vegetation reflectance could be called the first order approximation (Figure 3.8.9).

Most of the vegetative indices (Figure 3.8.10) defined by research in the field simply measure (in some normalized sense) the magnitude of the change between the visible region and infrared plateau as portrayed in zero'th order approximation (Figure 3.8.8).

One feature which has not been fully exploited in the past is the <u>position</u> of this change between absorbing and reflecting wavelengths. There can be a significant shift in the position of this transition depending upon the condition and/or the development stage of the vegetation. As an illustration, compare the reflected radiance curves for booted wheat (heads not emerged yet) and headed wheat (heads full emerged) in Figures 3.8.11 and 3.8.12 respectively. In the booted wheat spectrum, there is a peak in radiance which occurs just shy of the O_2 absorption band and is about equal to the maximum radiance at approximately 785 nm. In the headed wheat spectrum the position of the high slope region has shifted towards the red; the peak in radiance has also been shifted slightly to the red and the peak is noticeably lower than the maximum radiance

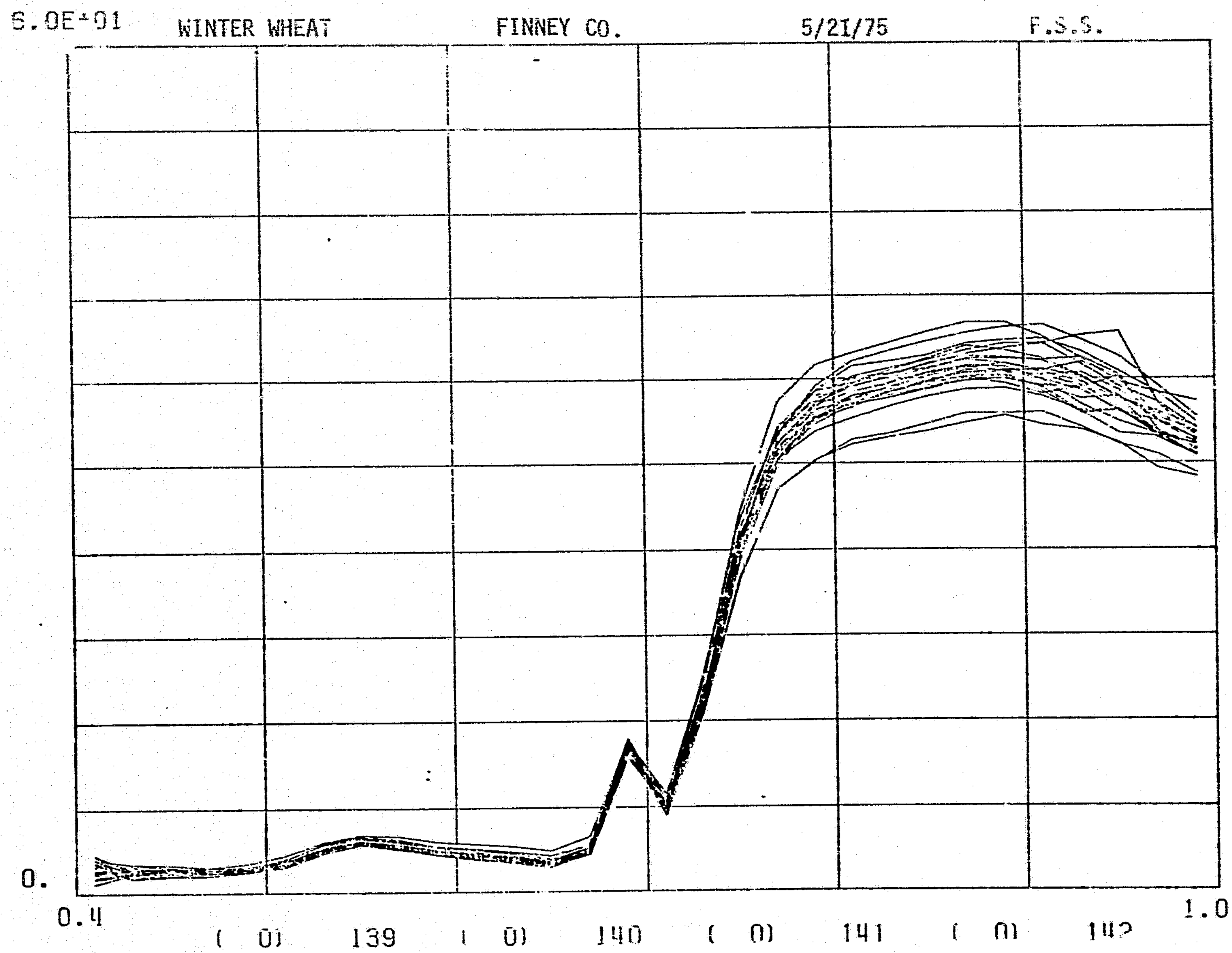

FIGURE 3.8.6 REFLECTANCE CURVES FOR WINTER WHEAT IN THE 0.4 TO 1.0 μm SPECTRAL REGION, FINNEY CO., KANSAS 5/21/75

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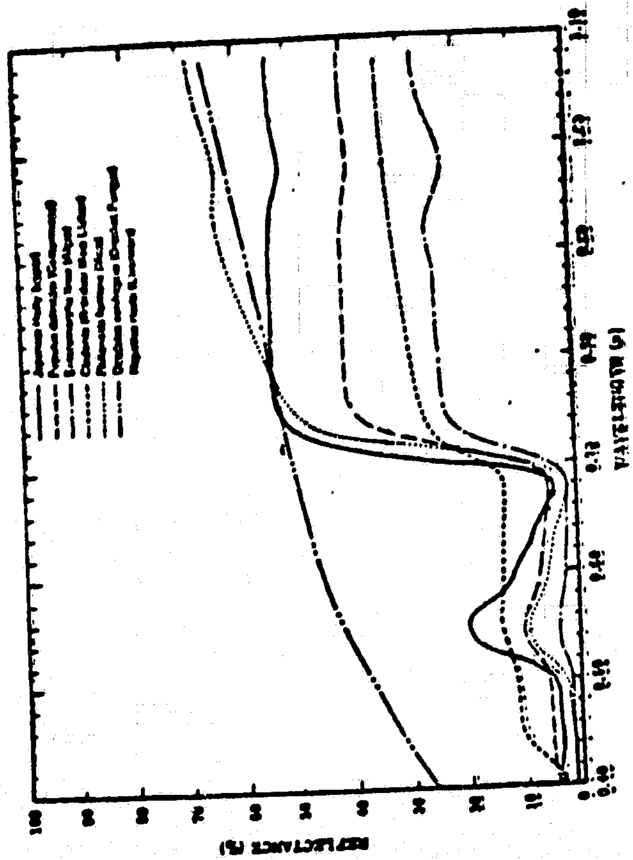

FIGURE 3.8.7 REFLECTANCE CURVES FOR OTHER SPECIES

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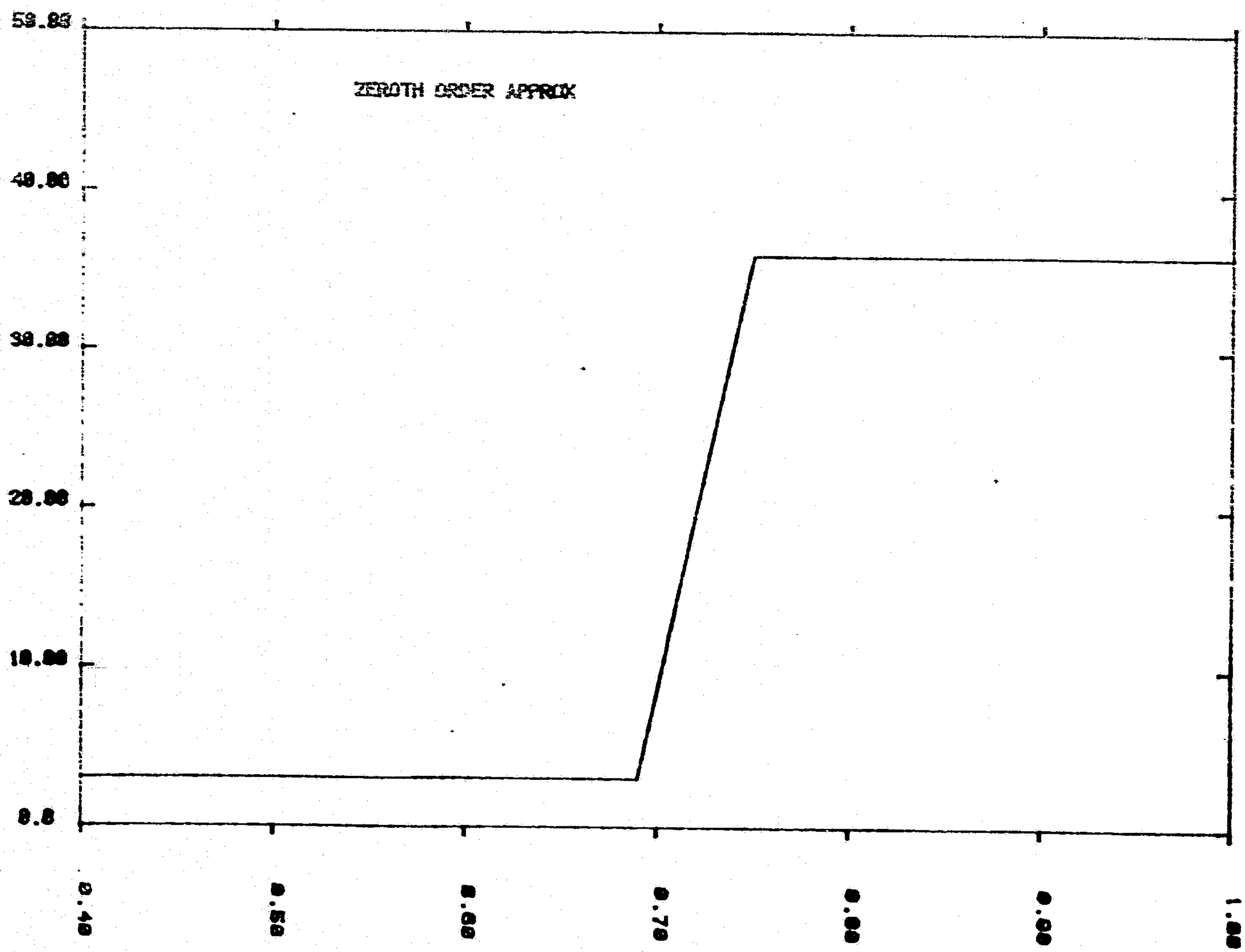

FIGURE 3.8.8 ZEROTH ORDER APPROXIMATION OF VISIBLE ABSORPTION TO IR REFLECTANCE

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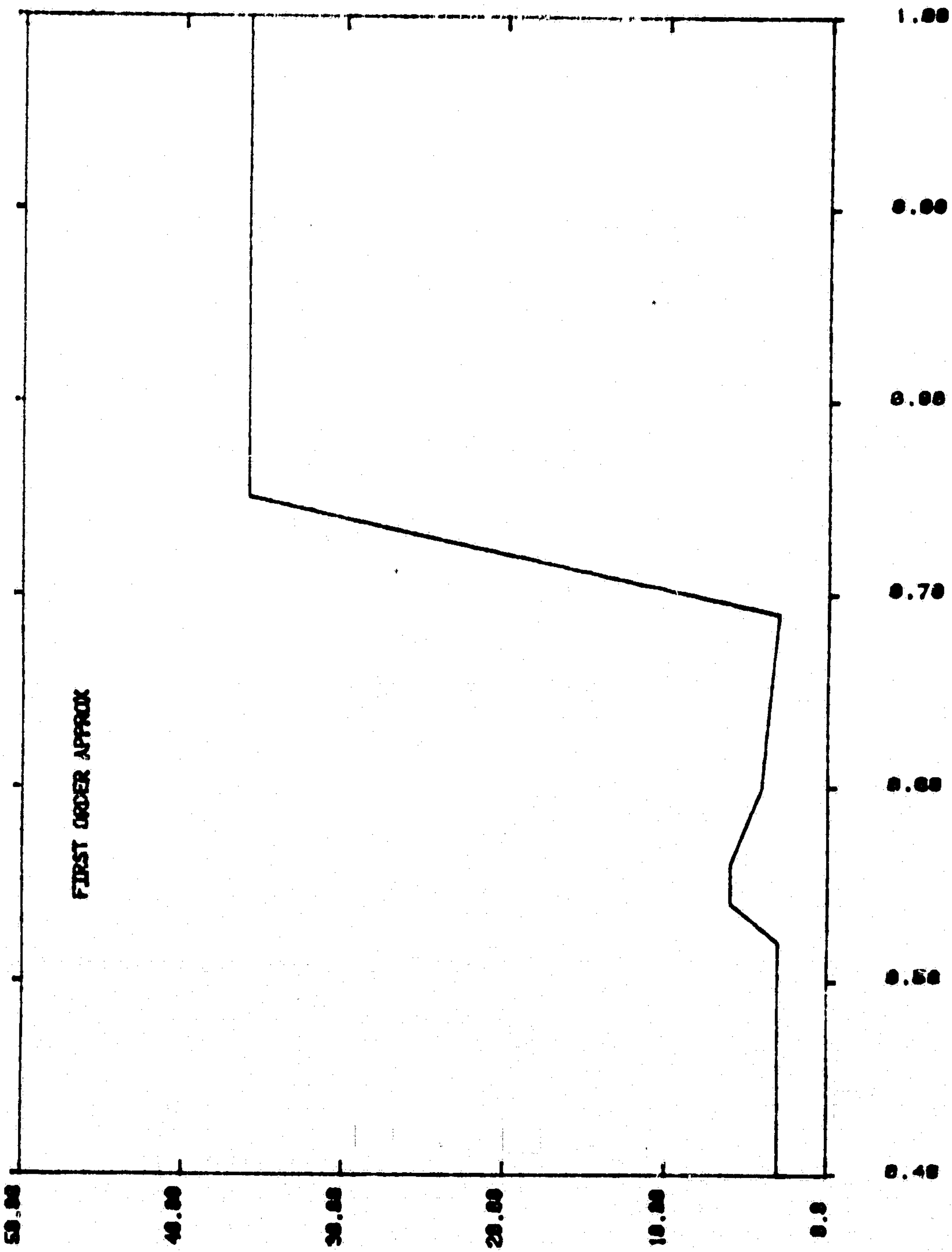


FIGURE 3.8.9 FIRST ORDER APPROXIMATION INCLUDING GREEN PEAK

VEGETATION INDICES

IR/RED	TM-4/3
VI	GREEN/RED
TVI	TM-4/5
PVI	TM-6/5
SBI	RS
GVI	FSS-RS

FIGURE 3.8.10 VEGETATION INDICES

BOOTED WHEAT

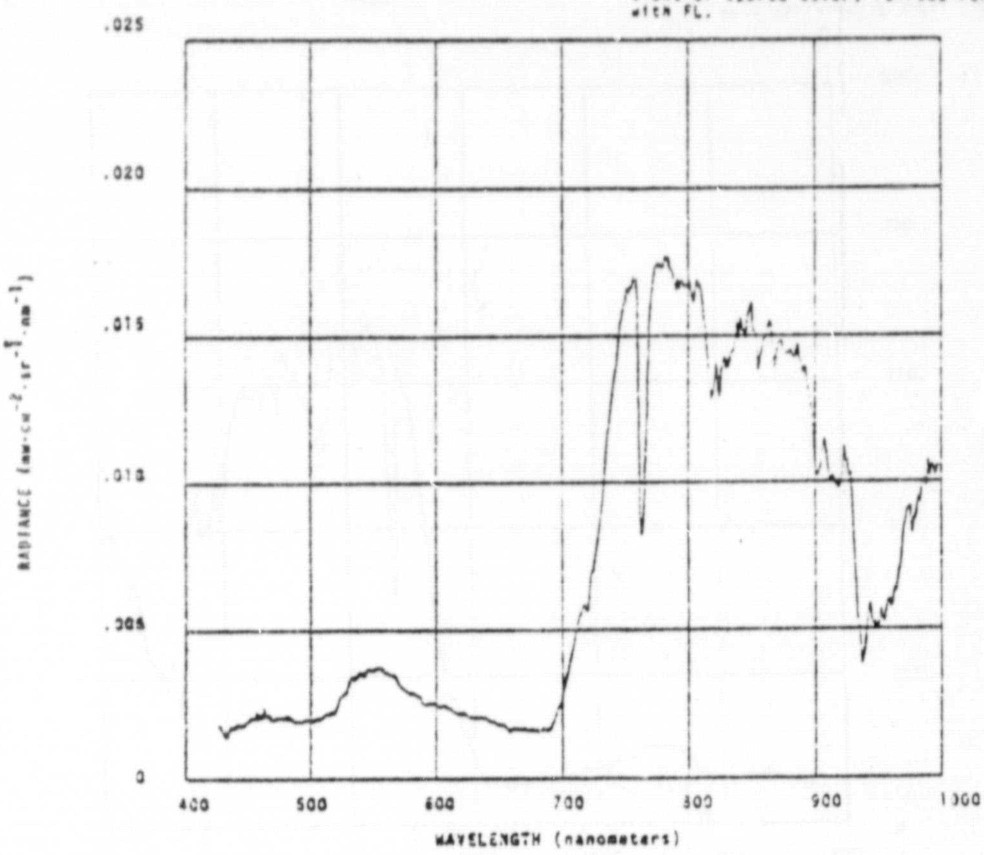
FIELD DESCRIPTION

12 to 14 inches high, 80 to 100% leaf cover, moderately thick patchy canopy. Heads not emerged, crop green. Soil wet. Imperial, silty clay.

PHOTO INTERPRETATION

Innomogeneous tone; texture is differential ranging from medium to coarse; density is differential ranging from medium to low; crop cover is in a diagonal pattern, probalby caused by subsurface drainage pipes producing striations of sparse cover; furrows run parallel with FL.

2492



10:34 AM 5/16/75

SUN ELEV = 70°

FIGURE 3.8.11 REFLECTED RADIANCE CURVES FOR BOOTED WHEAT (HEADS NOT EMERGED)

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2486-2503

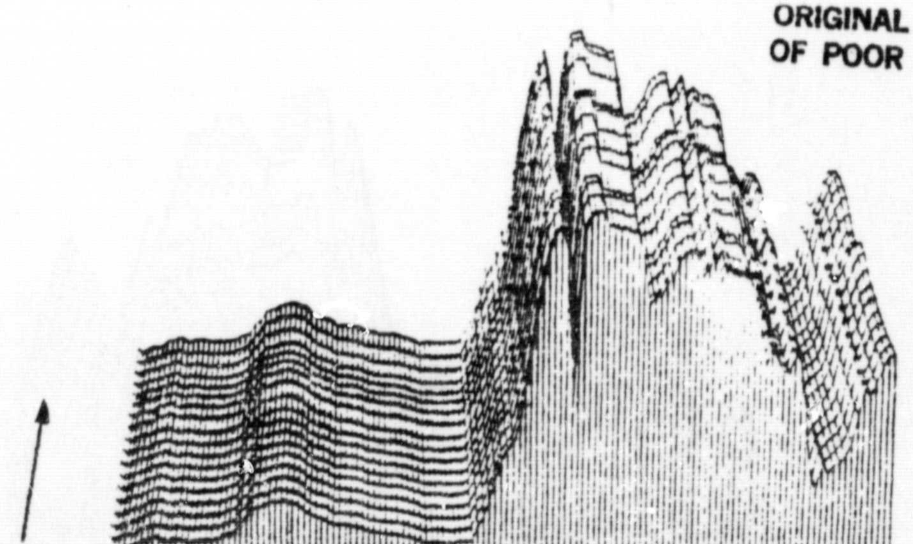

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Figure 3.8.12 (152)

HEADED WHEAT

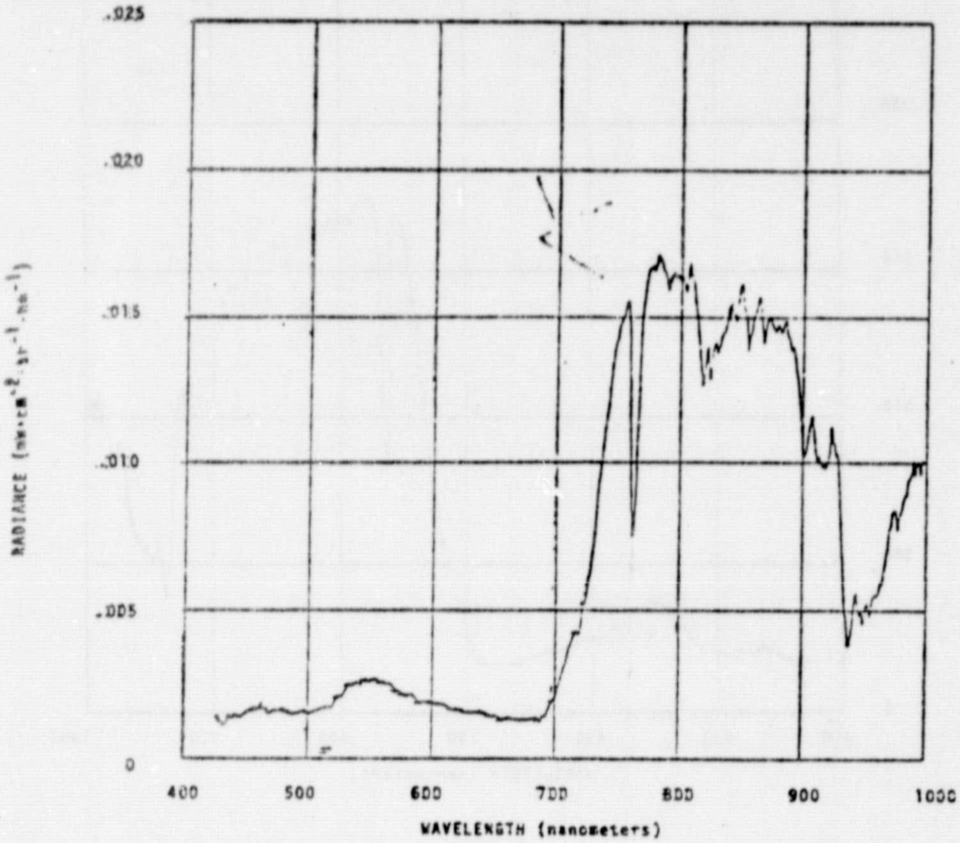
FIELD DESCRIPTION

36 to 30 inches high, 100% leaf cover, thick uniform canopy. Heads fully emerged and green. Soil dry. Imperial, light brown silty clay (7.5YR 6/4).

PHOTO INTERPRETATION

Homogeneous tone; no texture; high density; total cover.

2678



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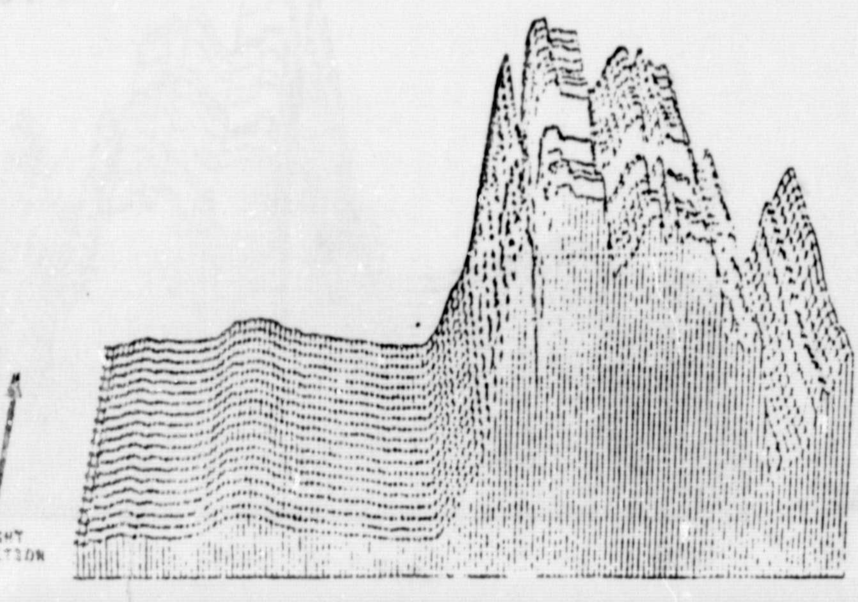
SUN ELEV = 68°

FIGURE 3.8.12 REFLECTED RADIANCE CURVES FOR HEADED WHEAT (HEADS FULLY EMERGED)

2664-2678



at 785 nm. This effect may also be exploited to distinguish between species by taking advantage of differences in crop state. As illustrated in Figure 3.8.13 which compares the reflection spectrum of headed wheat with that of alfalfa.

It would appear that a ratio of the reflected radiance at the reflectance maximum near 785 nm to that at the high slope region near 745 nm might be a useful parameter for vegetation analysis. Data collected over Kansas fields by William Collins using an airborne photospectrometer tends to confirm this. Figure 3.8.14 shows that, using the ratio of two bands with 10 nm bandwidths centered about 785 nm and 745 nm, irrigated wheat is distinct from alfalfa and both are distinguishable from corn, grain sorghum and non-vegetated soil. In this test, non-irrigated wheat fields resembled the alfalfa fields.

Increasing the bandwidth to 20 nm, the bandwidth which will be available on the MRS, does not seem to greatly harm the characterization of wheat compared to emergent corn and alfalfa. Figure 3.8.15 is a presentation of ratios of 20 nm bandwidth data collected with the FSS in Kansas. Again, the non-irrigated wheat fields are the most problematic. Unfortunately not many control (vegetated, but not wheat) fields were overflown by the FSS and hence these results are not conclusive on their own. However, since the Collins and FSS overflights occurred on the same day, it is possible to anticipate FSS derived measurements by comparing ratios calculated from both instruments over fields which were flown in common. Such a comparison is shown in Figure 3.8.16. The two ratios are very highly correlated suggesting that there will be little loss of information if 20 nm bandwidths are used.

Collins' ratio compares favorably with other measures of growth stage. One such measure (in the 0.4 to 1.0 μm spectral region) has been suggested by Park (Multispectral Temporal Analysis, General Electric IR&D Project Report, 1979) who used a ratio of simulated TM bands as vegetation index (Figure 3.8.17). Figures 3.8.18 and 3.8.19 show Collins' ratio and Park's ratio respectively versus growth stage of wheat. Both ratios appear to be closely related to the growth stage.

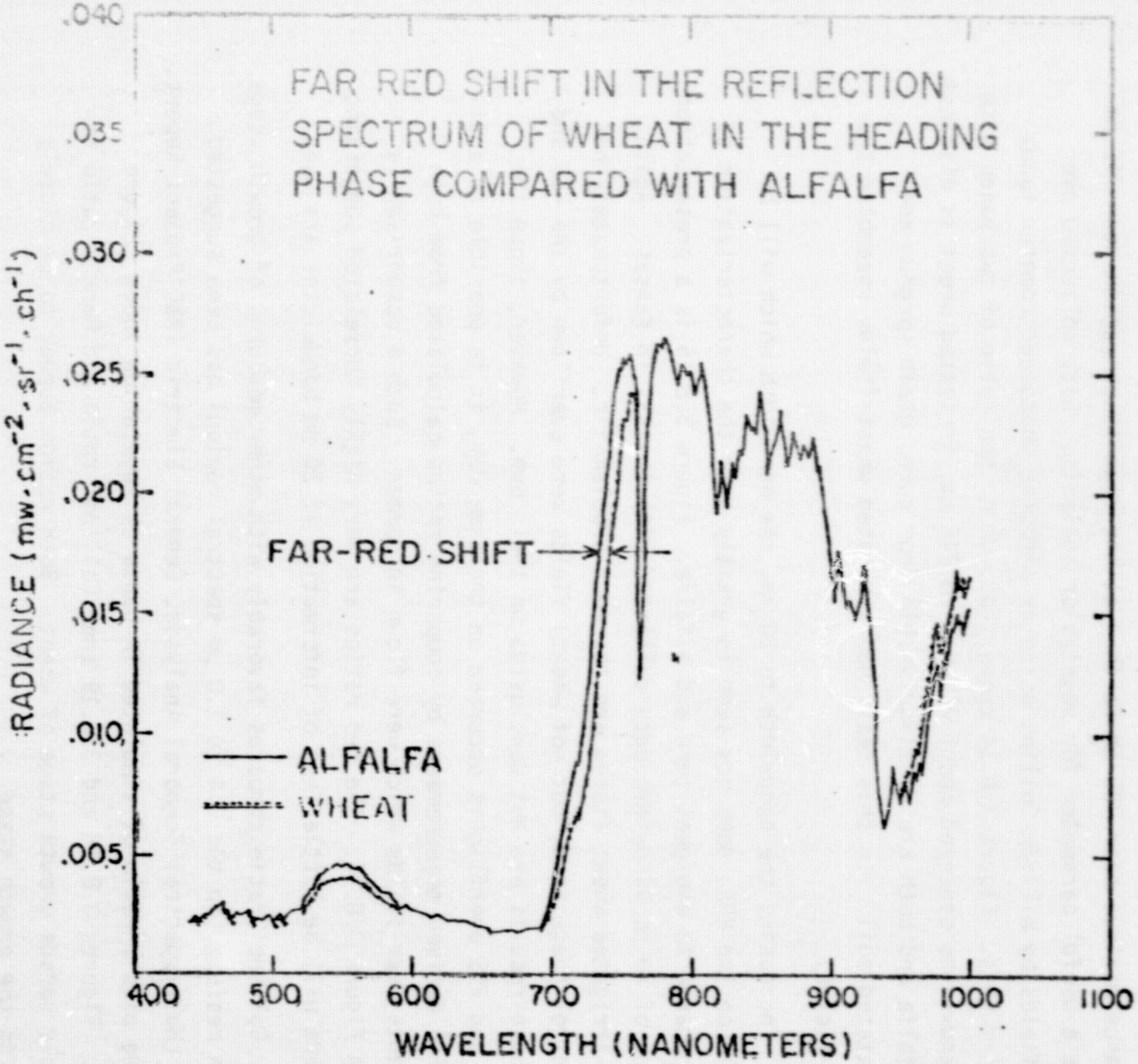


FIGURE 3.8.13 COMPARISON OF REFLECTION SPECTRUM OF HEADED WHEAT AND ALFALFA

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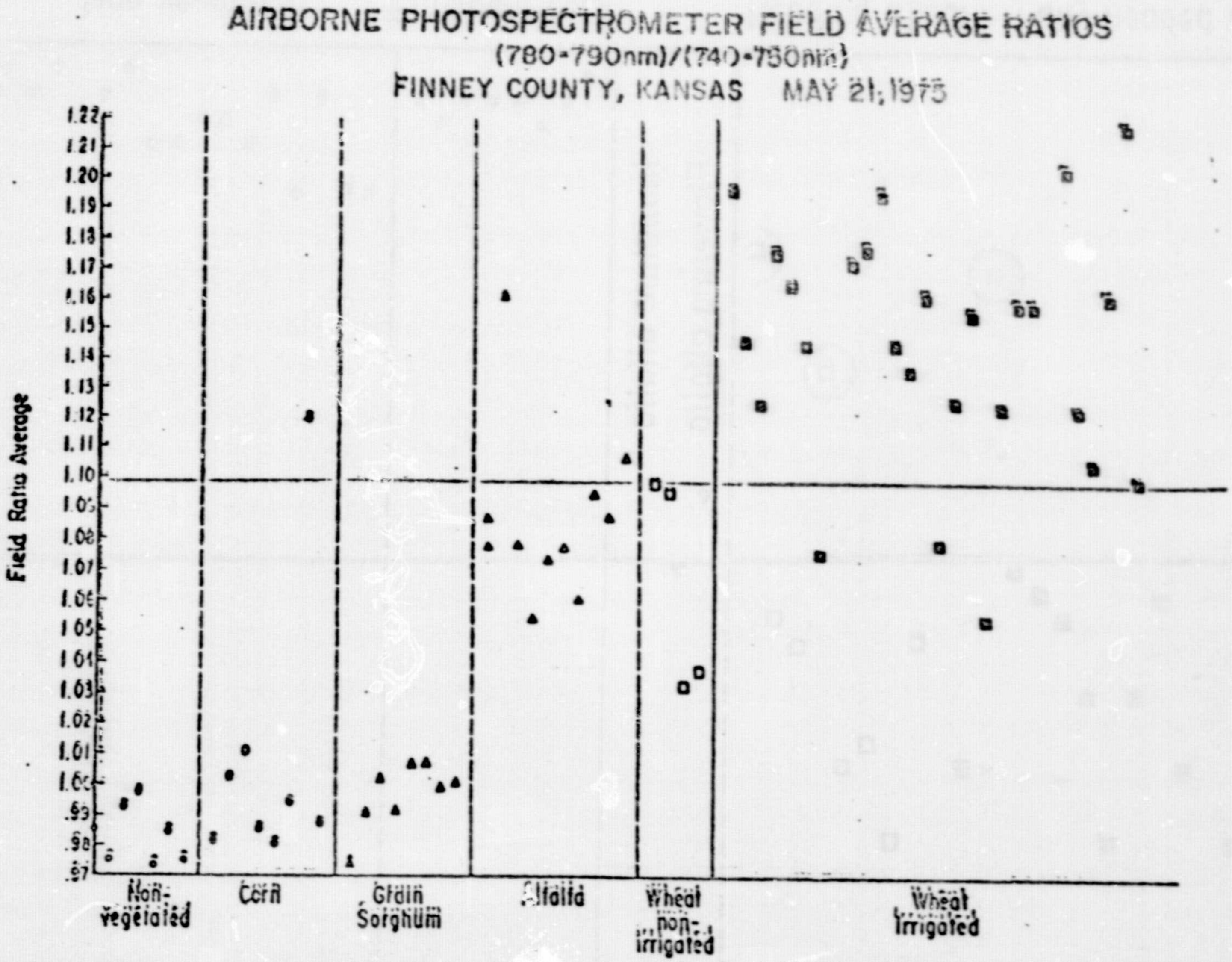
AIRBORNE PHOTOSPECTROMETER FIELD AVERAGE RATIOS
(780-790nm)/(740-750nm)
FINNEY COUNTY, KANSAS MAY 21, 1975
Field Ratio Average
1.22
1.21
1.20
1.19
1.18
1.17
1.16
1.15
1.14
1.13
1.12
1.11
1.10
1.09
1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1.00
.99
.98
.97
Non-vegetated
Corn
Grain Sorghum
Alfalfa
Wheat non-irrigated
Wheat Irrigated

Figure 3.8.14

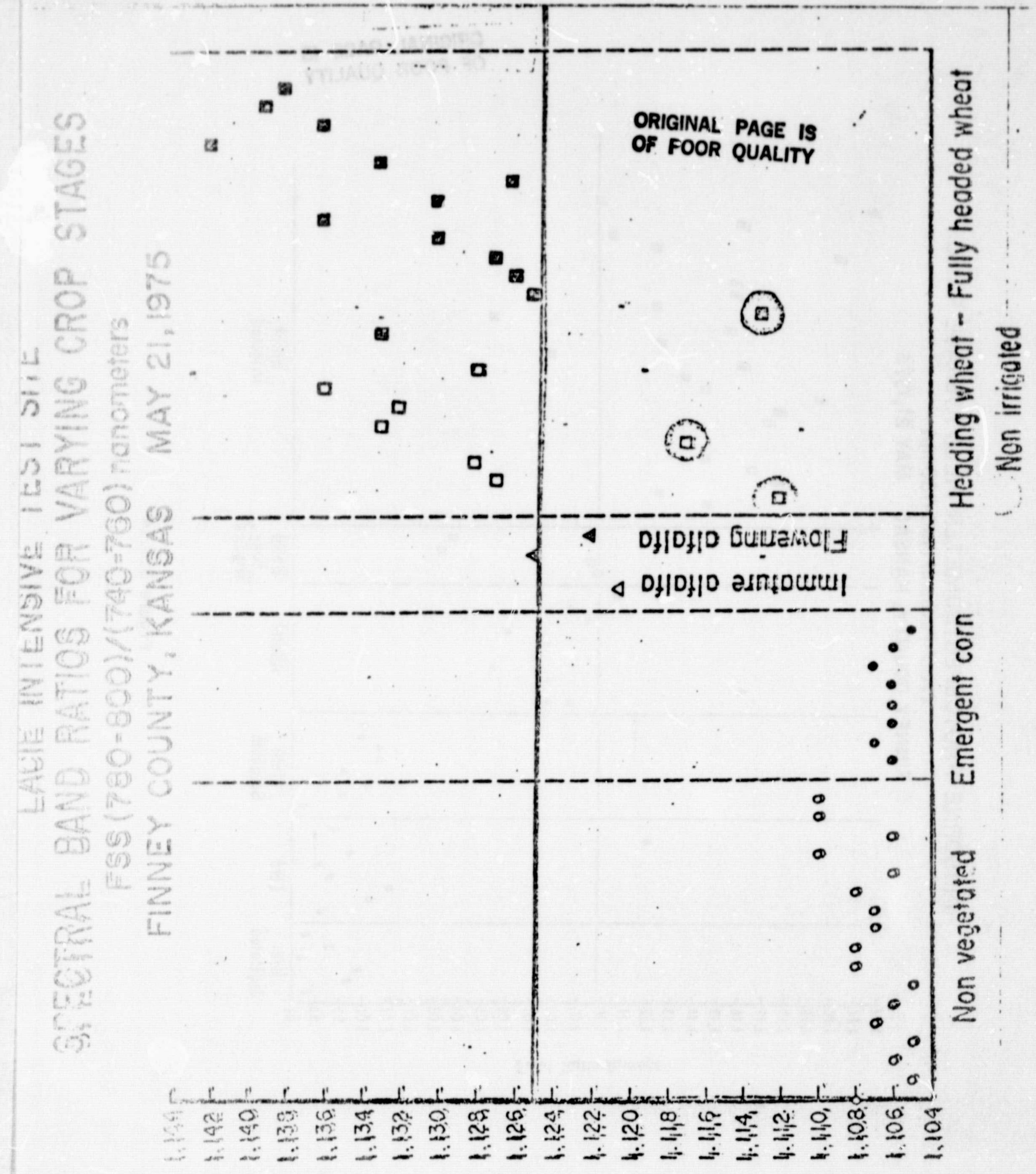

FIGURE 3.8.15

C-3

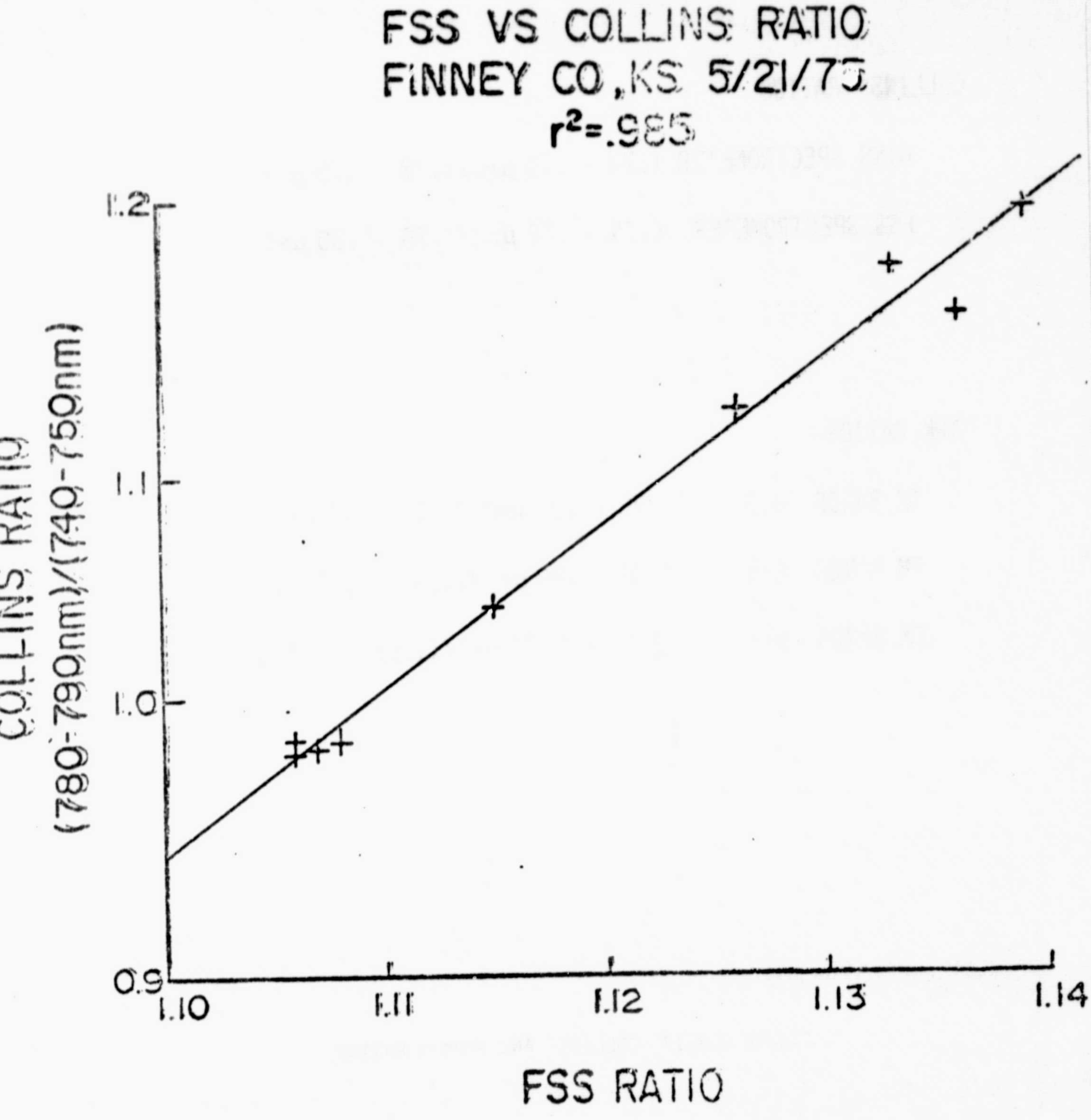
FSS VS COLLINS RATIO
FINNEY CO.,KS 5/21/75
r^2=.985
1.2
1.1
1.0
0.9
COLLINS RATIO
(780-790nm)/(740-750nm)
1.10
1.11
1.12
1.13
1.14
FSS RATIO
(780-800nm)/(740-760nm)

FIGURE 3.8.16

COLLINS' RATIOS

GISS SPECTROMETER (.74 - .75 μM)/(.78 - .79 μM)

FSS SPECTROMETER (.74 - .76 μM)/(.76 - .80 μM)

PARK RATIOS

TM BANDS	4:3	(.76 - .90 μM)/(.63 - .69 μM)
TM BANDS	4:5	(.76 - .90 μM)/(1.55 - 1.75 μM)
TM BANDS	6:5	(2.08 - 2.35 μM)/(1.55 - 1.75 μM)

FIGURE 3.8.17 COLLINS' AND PARK'S RATIOS

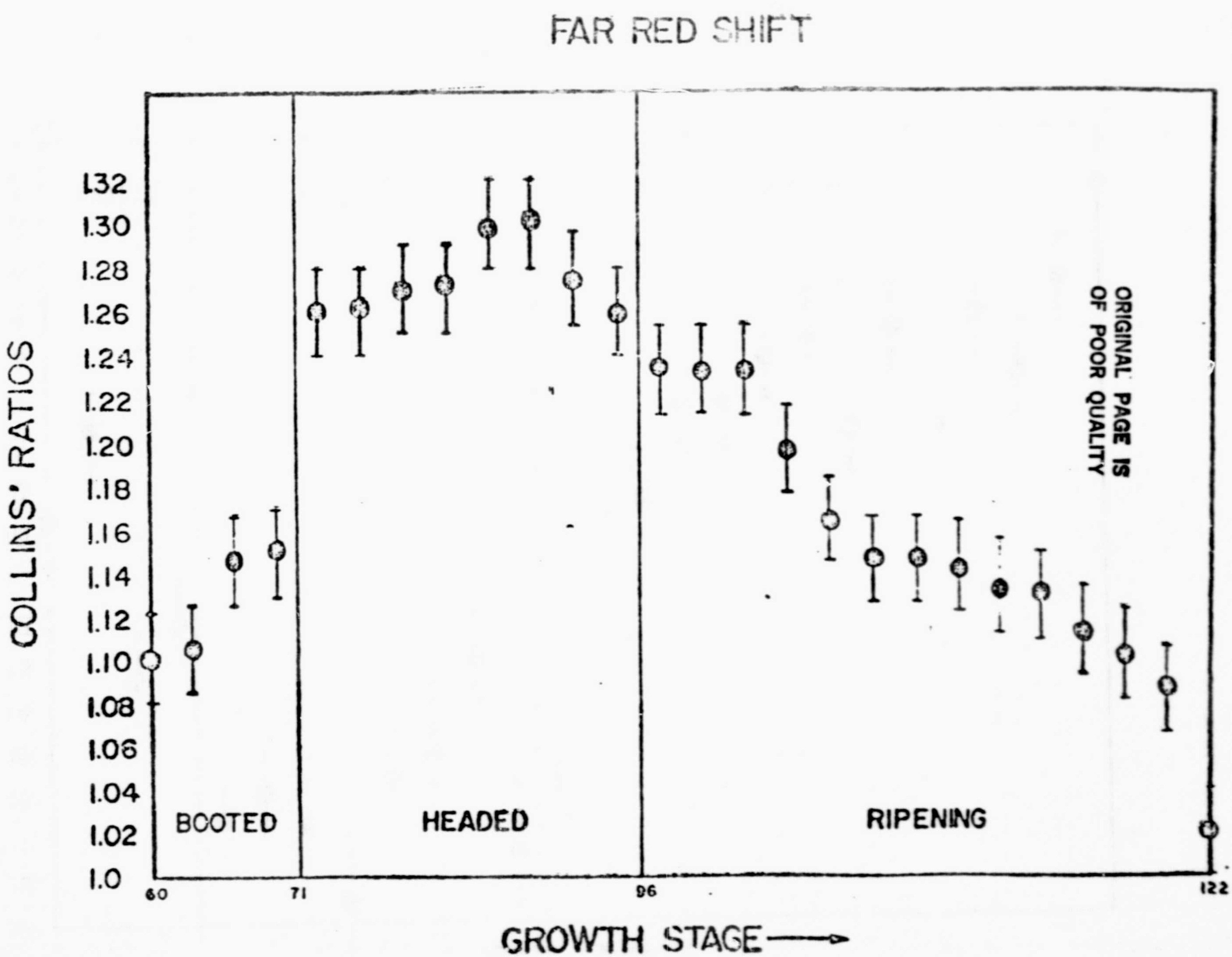

FIGURE 3.8.18 COLLINS' RATIO VERSUS GROWTH STAGE OF WHEAT

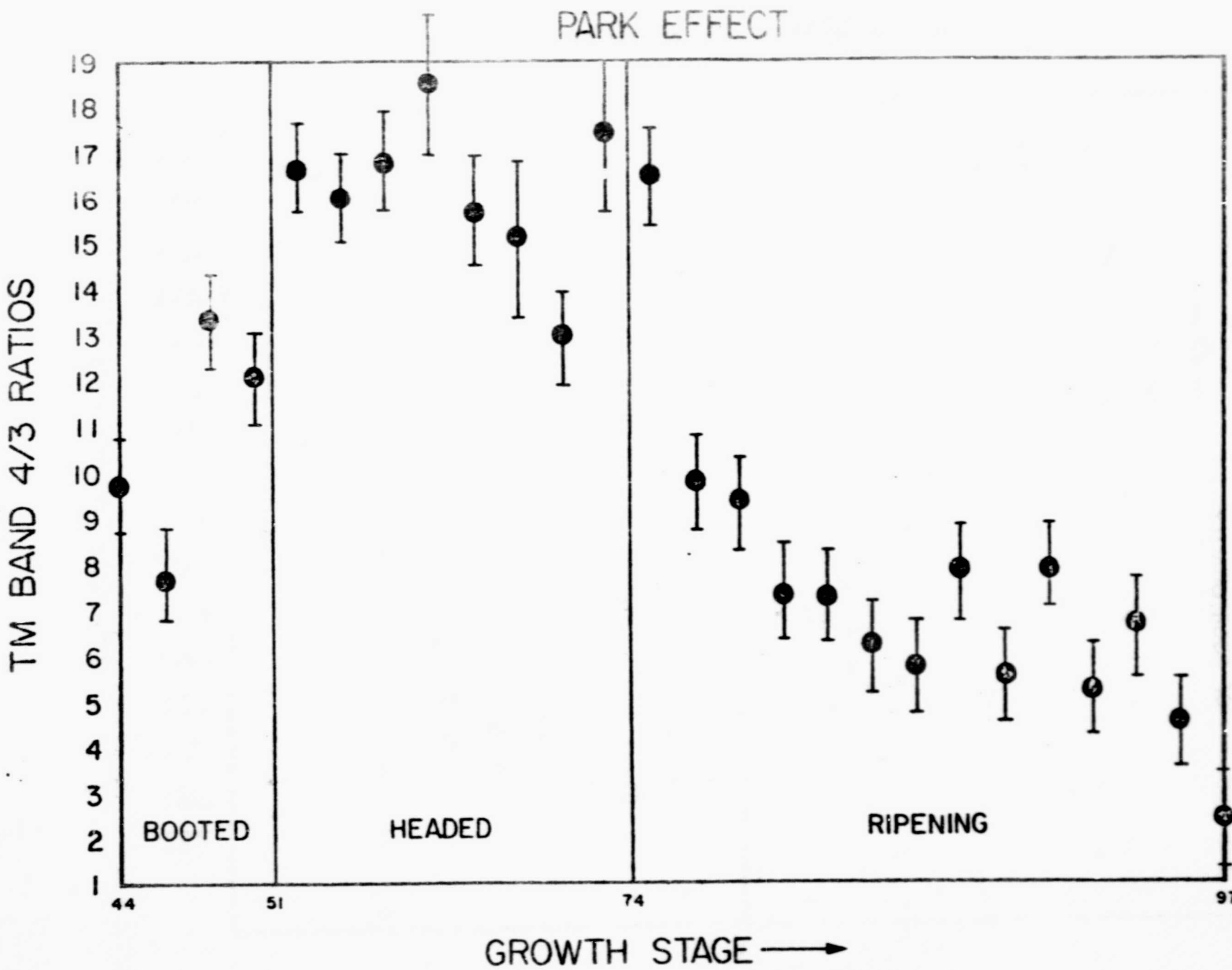

FIGURE 3.8.10 PARK'S RATIO VERSUS GROWTH STAGE OF WHEAT

The general conclusion is that both the position of transition from absorption to reflection and traditional measures of relative degree of absorption are important (and to some degree independent) sources of information relating to plant stage. The Collins' ratio is pigment sensitive and the traditional indices are biomass and pigment sensitive.

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3.9 SPATIAL RESOLUTION CONSIDERATIONS

DR. LEE MILLER

One of the major concerns with satellite remote sensing is the spatial resolution. Considering the continued interest in increasingly better spatial resolution, it is surprising that very little research has been undertaken to establish the resolution requirements for remote sensing applications. Most of the stated requirements for spatial resolution seem to be estimates based more on intuition than on experimental evidence. Some of these estimates are presented in Figures 3.9.1, 3.9.2, 3.9.3, and 3.9.4. These estimates actually seem quite reasonable in spite of the lack of research.

In looking at these tables one should keep in mind that, assuming a circular target of diameter d, the IFOV of the sensor can be no larger than $\sim 0.4d$ to insure that at least one pixel falls entirely within the target.

Figures 3.9.5 and 3.9.6 show classification accuracy as a function of spatial resolution for several types of classification problems. These figures suggest that classification accuracy may not necessarily improve with increased spatial resolution. These graphs were devised by considering classification using spectral characteristics only. The improvement in classification which might be possible if texture were considered was not taken into account.

Cheng et al. (1979) made a study of the size distribution of tree crown diameters for several varieties of pine. The results are shown in Figure 3.9.7. It is clear from this chart that the 15m resolution of the MRS will not be sufficient to resolve these trees. In fact, individual trees will not be resolved until the resolution approaches 5m. The term "resolving" is used here in the sense that the resolution element is roughly the same size or smaller than the individual target elements (trees).

In another study, Theis (1978) considered the value of orchard crops when the size of the tree and the optimal planting space was taken into account. Figure 3.9.8 shows the average sizes of mature tree crown diameters for several orchard crops. As with the study on pine trees, it seems that for most of these crops, individual trees will not be resolved until the resolution is considerably better than 15m. These results bear out the EIFOV for forest typing presented in Figure 3.9.1.

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Table A-1

Agriculture/Forestry/Geography Requirements

	Specific Application and Parameters to be Measured	Desired Time of Acquisition	EIFOV (Meters)	Sequential Coverage (Yes or No) ( ) Indicates Probable Coverage Required	Estimated Working Scale	Frequency for Determination of Application	Probable Platform
Multispectral Sampling Photography or Imagery	General Guide Lines						
	1st level (Information)		50-100		1:1,000,000	- - -	S/C
	2nd level (As in Forest Typing)		5-10		1:50,000	- - -	A/C, S/C
	3rd level (Individual Species Identif.)		< 1-2		1:[illegible] to 1:4,000		A/C
	Forest Inventory						
	1 1st level, Forest-Nonforest	Winter, Early Spring	50-100	Yes (2)	1:250,000	5 yrs.	S/C
	2 2nd level, Forest Typing	Spring & Winter	2-5	Yes (2)	1:50,000	5 yrs.	A/C
	3 3rd level, Tree Counts, Crown diam., Individual Species Identification	Summer	< 1	No (1)	1:2,000 to 1:4,000	5 yrs.	A/C
	4 4th level, Ground						
	Crop Acreage and Production Predictions						
	1 1st level, Crop-Noncrop	Growing Season	50-100	Yes (continuous)	1:250,000	Annual	S/C
	2 2nd level, Crop Types, Crop, Pasture, Orchard	Growing Season	5-10	Yes (4 flights per yr.)	1:100,000	Annual	A/C
	3 3rd level, Crop Identification and Stress	Growing Season	< 1	Yes (4 flights)	1:2,000	Annual	A/C
	4 4th level, Ground						
	Range Inventory						
	1 1st level, Range-Nonrange		50-100	Yes	1:250,000	5 yrs.	S/C
	2 2nd level, Range Types		2-5	Yes (twice a yr.)	1:50,000	5 yrs.	A/C
	3 3rd level, Range Identif. and Trend		< 1	No (once a yr.)	1:600	5 yrs.	A/C
	4 4th level, Ground						
Commercial Data Needs	1 Coastline	Early Summer	50-100	No (1)	1:500,000	5 yrs.	S/C
	2 Waterline	Various	50-100	Yes (2)	1:500,000	Annual	S/C
	3 Snowline	Winter	50-100	Yes (6)	1:500,000	Biweekly	S/C
	4 Desertline	Various	50-100	No (1)	1:500,000	5 yrs.	S/C
	5 Grassland - Brushland Interface	Spring & Fall	50-100	Yes (2)	1:500,000	5 yrs.	S/C
	6 Brushland - Timberland Interface	Spring	50-100	Yes (3)	1:500,000	5 yrs.	S/C
	7 Grassland - Timberland Interface	Spring & Fall	50-100	Yes (2)	1:500,000	5 yrs.	S/C
	8 Bare Soil vs. Vegetated Areas	Spring & Summer	30-50	Yes (3)	1:100,000	Annual	S/C
	9 Major Roads, Railroads and Waterways	Summer & Winter	30-50	Yes (2)	1:100,000	Annual	S/C
	10 Cropland vs. Non-Cropland	Growing Season	50-100	Yes (4)	1:250,000	Annual	S/C
	11 Plant Stress Detection	Growing Season	2-5/30-50	Yes (4)	1:10,000 1:100,000	Weekly	A/C S/C
	12 Farmsteads	Growing Season	20-30	No (1)	1:100,000	5 yrs.	A/C, S/C
	13 Mature Orchard Trees	Growing Season	2-5	Yes (4)	1:50,000	Annual	A/C
	14 Forest Engineering	Winter & Summer	5-10	Yes (2)	1:100,000	Annual	A/C
	15 Areal Extent of Water Surfaces	Summer	5-10	Yes (2)	1:50,000	Annual	A/C
	16 Crop Species Iden. in Fields	Growing Season	2-5/30-50	Yes (4)	1:50,000	Annual	S/C, A/C
	17 Areal Meas. of Fields on Farms	Growing Season	2-5	No (1)	1:50,000	Annual	A/C
	18 Urbanized Areas	Various	50-100	No (1)	1:250,000	Annual	S/C
	19 Land Use Change	Various	30-50	Yes (6)	1:250,000	Annual	S/C
	20 Areal Extent of Single City	Various	30-50	No (1)	1:250,000	Annual	S/C
	21 Functional Morphology	Winter & Summer	5-10	Yes (2)	1:100,000	Annual	A/C
	22 Detailed Urban Sites	Winter & Summer	1-5	Yes (2)	1:25,000	Annual	A/C
	23 Emergency or Disaster	On Command	1-5	Yes (4)	1:50,000	As Needed	A/C

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Figure 3.9.1

ATTACHMENT B

GEOLOGY REQUIREMENTS

Table B-1 lists the important geologic applications and some of the data attributes needed for these applications. The figures that follow are keyed to the number designation in Table B-1.

Table B-1

Specific Applications	Application Designation	EIFOV (meters)	Sequential Coverage*	Estimated Scale	Frequency for determination and Application	Platform	Multispectral
Structural geology Faults, folds, lineaments	1 2	50-80 10-20	Yes S/A & V Yes S/A & V	1:250,000- 1:1,000,000 1:24,000	Varies with development of science ~5	S/C A/C	Yes Yes
Geomorphology *(landform classification)	3 4	50-80 10-20	Yes S/A No	1:250,000- 1:1,000,000 1:24,000	As above	S/C A/C	No No
Lithologic mapping	5 & 6	50-80 10-20	Yes V "	1:1,000,000- 1:250,000 1:24,000	Once Once	S/C A/C	Yes Yes
Geologic Hazards Faults	7 8	50-80 10-20	Yes S/A V Yes S/A V	1:1,000,000- 1:250,000 1:24,000	Once/decade Once/year	S/C A/C	Yes Yes
Landslides Volcanoes	9 10	10-20 100-200	Yes V Yes ΔT**	1:24,000 1:1,000,000	Once/year Once/year	 S/C	Yes, No
**(Possibly also SO_2)							
Shoreline changes	11 & 12	30-50 5-10	Yes, varies with location PC	1:250,000 1:24,000	Varies Varies	S/C A/C	Yes Yes
Geochemical (plant stress)	13 & 14	50-80 10-20	Yes V Yes V†	1:250,000 1:24,000	Once Once	S/C A/C	Yes Yes
†(Possibly also luminescence)							
Gross physical Properties	15 to 17	1000-2000 50-80 10-20	Yes S/A Yes S/A No	1:1,000,000 1:250,000 1:24,000	Once Once Once	S/C S/C A/C	Yes Yes Yes

*Reason for sequential coverage

S/A, changing sun angle

ΔT, change in temperature

S/C, Spacecraft

A/C, Aircraft

PC, physical change

V, vegetation change

51

Figure 3.9.2

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Table C-1

Hydrology Requirements

Applications	EIFOV Coverage	Sequential Coverage	Estimated Scale	Frequency Determination	Platform
1. Delineation of land-water boundaries	40-60	Yes	1:100,000	weekly,	S/C
	-10	Yes	1:10,000-1:100,000	as required	A/C
2. Delineation of hydrologically related terrain features	30-50	Yes	1:100,000	bi-weekly	S/C
	1-10	Yes	1:10,000-1:100,000	as required	A/C
3. Hydrodynamics, including floods, and estuaries	10-30	Yes	1:100,000	weekly, on command for cloud coverage	S/C
	1-10	Yes	1:10,000-1:100,000	as required	A/C
4. Water quality-evaluation	30-70	Yes	1:100,000	weekly	S/C
	1/3	Yes	1:10,000-1:100,000	as required	A/C
5. Snow cover and runoff	50-80	Yes	1:250,000	daily	S/C
	10-50	Yes	1:100,000	Daily in season	A/C

Figure 3.9.3

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ATTACHMENT E

MARINE AND OCEAN APPLICATIONS

Table E-1 presents the important applications in marine and ocean science. The figures that follow are keyed to the number/letter designation indicated for each application in Table E-1

Table E-1

Sensor Geometrical Needs for Marine and Ocean Applications

Marine and Ocean Applications*	EIFOV (Meters on Ground Unless Otherwise Specified)	Field of Coverage (km) (Minimum Swathwidth)	Max Oblique Pointing Angle (Degrees)	Sample or Contiguous Coverage (S or C)
(1) Currents				
(a) Coastal Current Mapping	0-100	200 km	30°	C
(b) Coastal Current Measurement	3-10	40 km	nadir	C
(c) Turbidity and Transport	50-100	200 km	30°	C
(d) Global Mapping	1-10 km	400 km	20° **	C
(2) Sea Ice Surveillance	30-100	200 km	30°	C
(3) Biological Processes				
(a) Assessment	1-2 km	400 km	20° **	C
(b) Coastal Pollution Detection	30-50	200 km	45°	C
(c) Pollution Environmental Impact	30-300	200 km	45°	C
(d) Global Ecosystem Analysis	1-10 km	400 km	20° **	C
(4) Coastal Geological Processes				
(a) Shoreline Mapping & Shoals	30-50	200 km	nadir	C
(b) Wetlands Inventory	30-50	200 km	nadir	C
(c) Bathymetry & Bottom Topography	50-100	200 km	nadir	C
(d) Mean High/Low Water	3-10	40 km	nadir	C

*Identifying number and alphabetical designations are referred to by Figures E-1 and E-2.

**10 - 20 degree angle away from nadir is desired to look away from the sun side of the spacecraft.

Figure 3.9.4

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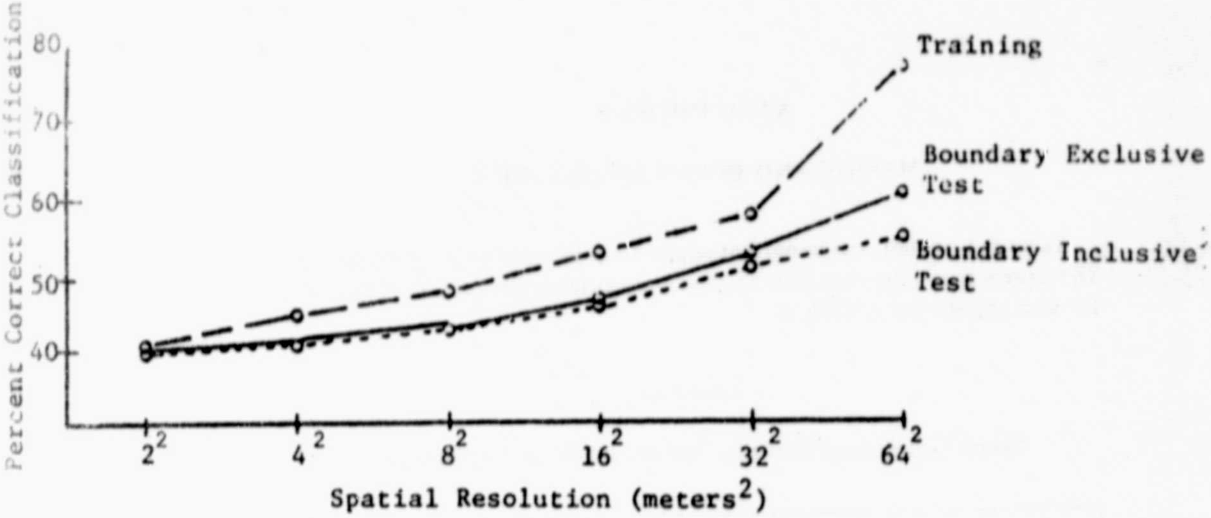

FIGURE 4. CLASSIFICATION ACCURACY PLOTTED AS A FUNCTION OF SPATIAL RESOLUTION FOR CONDITION CLASSES OF DATA SEGMENT 1

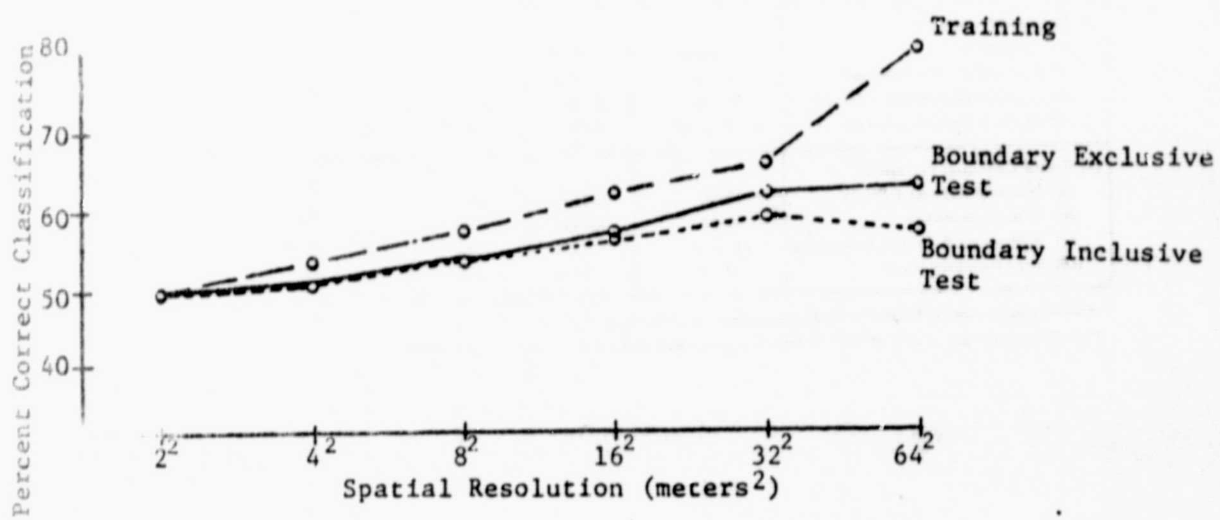

FIGURE 5. CLASSIFICATION ACCURACY PLOTTED AS A FUNCTION OF SPATIAL RESOLUTION FOR GROWTH STAGES OF DATA SEGMENT 1

Figure 3.9.5

BY SADOWSKI + SARNO 1976
ERIM-109600-71-F

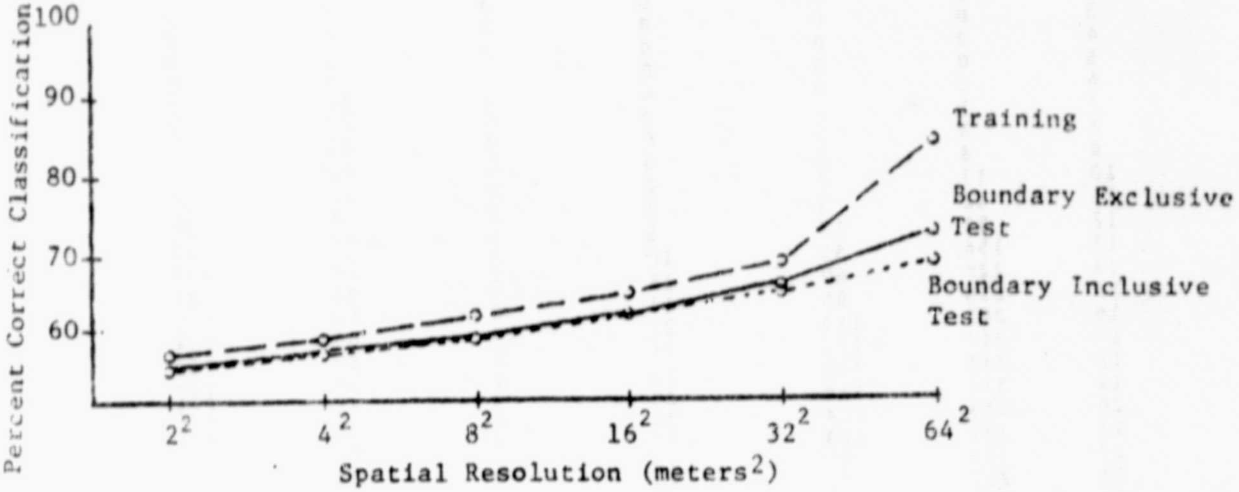

FIGURE 6. CLASSIFICATION ACCURACY PLOTTED AS A FUNCTION OF SPATIAL RESOLUTION FOR COVER TYPES OF DATA SEGMENT 1

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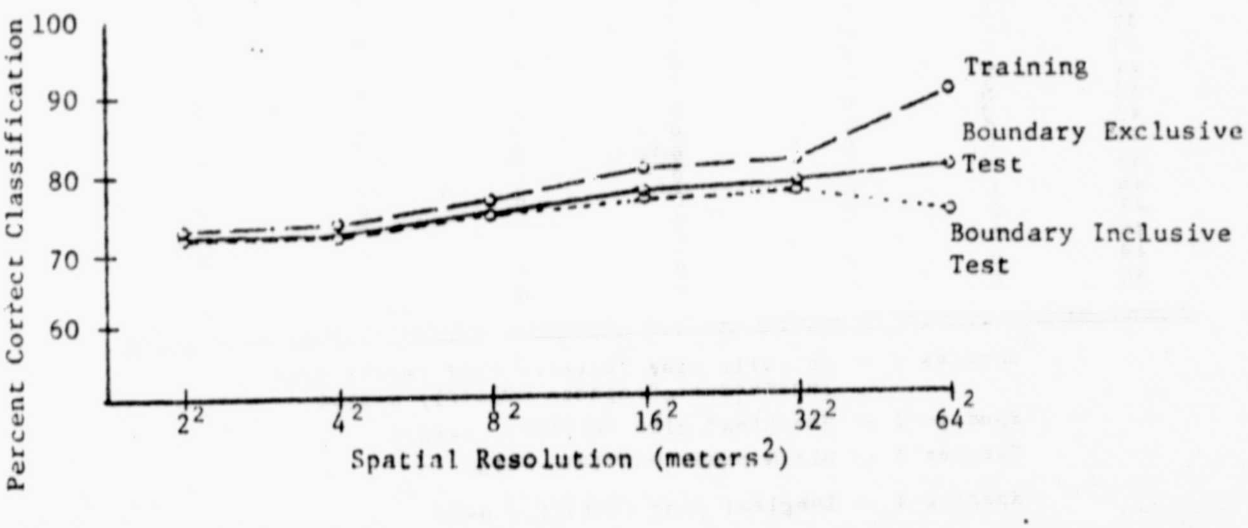


FIGURE 7. CLASSIFICATION ACCURACY PLOTTED AS A FUNCTION OF SPATIAL RESOLUTION FOR PHYSIOGNOMY OF DATA SEGMENT 1

Figure 3.9.6

Frequency Table
Tree Crown Diameters in Feet

C.D. (feet)	Species 1*	Species 2	Species 3	Species 4	Species 5	Species 6
1	0	0	0	0	1	0
2	0	0	0	0	0	1
3	0	0	0	0	0	0
4	0	0	0	0	1	0
5	0	0	0	0	7	0
6	0	0	0	0	16	0
7	1	1	0	0	27	0
8	3	0	0	0	29	3
9	8	1	0	0	42	9
10	13	2	0	0	71	20
11	42	5	2	0	76	38
12	88	18	5	0	92	91
13	156	55	10	0	90	153
14	229	69	18	0	64	181
15	256	96	14	0	85	213
16	292	113	27	0	68	264
17	347	155	31	0	59	267
18	343	118	30	2	55	197
19	374	118	39	6	43	162
20	383	124	28	1	47	118
21	301	120	40	7	31	93
22	316	81	40	5	23	53
23	257	75	32	1	16	56
24	235	62	32	1	22	37
25	235	39	20	0	12	26
26	222	25	23	1	5	20
27	175	15	15	1	7	7
28	173	12	10	0	3	3
29	150	6	8	0	1	3
30	119	4	4	0	2	2
31	103	3	1	0	1	0
32	74	1	2	0	0	2
33	62	1	3	0	0	0
34	55	2	5	0	0	0
35	37	0	0	0	0	0
36	37	0	0	0	0	1
37	28	0	0	0	0	0
38	14	0	0	0	0	0
39	17	0	0	0	0	0
40	7	0	0	0	0	1
41	5	0	0	0	0	0
42	4	0	0	0	0	0
43	1	0	0	0	0	0
44	1	0	0	0	0	0
45	0	0	0	0	0	0
46	1	0	0	0	0	0
47	0	0	0	0	0	0
48	0	0	0	0	0	0
49	0	0	0	0	0	0
50	4	0	0	0	0	0

*Species 1 -- Loblolly pine (Western Gulf Forest Tree Improvement Project--WGFTIP), n=5168.

Species 2 -- Shortleaf pine (WGFTIP), n=1321

Species 3 -- Slash pine (WGFTIP), n=439

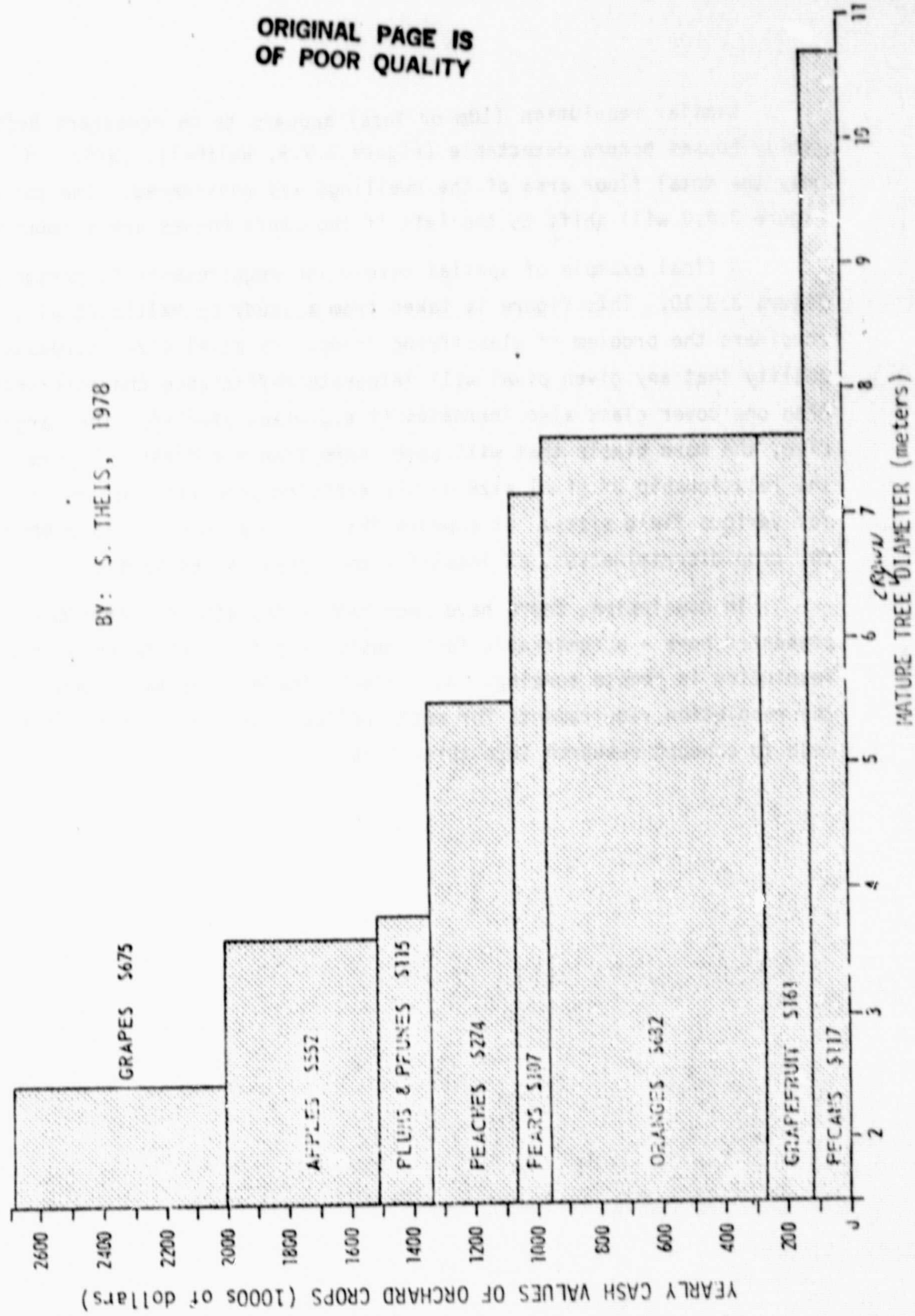
Species 4 -- Longleaf pine (WGFTIP), n=25

Species 5 -- Ponderosa pine (Arizona), n=996

Species 6 -- Slash pine (Georgia and Florida), n=2021

BY T. CHENG, M. MATHEWS, + R. MAGGIO 1979

Figure 3.9.7


BY: S. THEIS, 1978
GRAPES $675
APPLES $552
PLUMS & PRUNES $115
PEACHES $274
PEARS $107
ORANGES $632
GRAPEFRUIT $161
PECANS $117
YEARLY CASH VALUES OF ORCHARD CROPS (1000s of dollars)
MATURE TREE CROWN DIAMETER (meters)
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
2
3
4
5
6
7
8
9
10
11

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Similar resolution (10m or less) appears to be necessary before single-family houses become detectable (Figure 3.9.9, Walthall, 1979). In this study only the total floor area of the dwellings was considered. The curve in Figure 3.9.9 will shift to the left if two story houses are accounted for.

A final example of spatial resolution requirements is presented in Figure 3.9.10. This figure is taken from a study by Malila et al., 1976, which considers the problem of classifying crops. As pixel size increases, the probability that any given pixel will integrate reflectance characteristics for more than one cover class also increases (i.e., mixed pixels). The larger the pixel size, the more pixels that will cover more than one class. Figure 3.9.10 shows the relationship of pixel size on the expected proportion of multiclass pixels for various field sizes. It appears that a 15m resolution is probably adequate for crop discrimination, at least for the Kansas sites considered.

In conclusion, there have been rather few studies performed of the sort presented here - a remarkable fact considering the importance placed on spatial resolution in remote sensing. As a result there is no solid basis for fixing the resolution requirements for most applications. A serious effort should be made to conduct research into this topic.

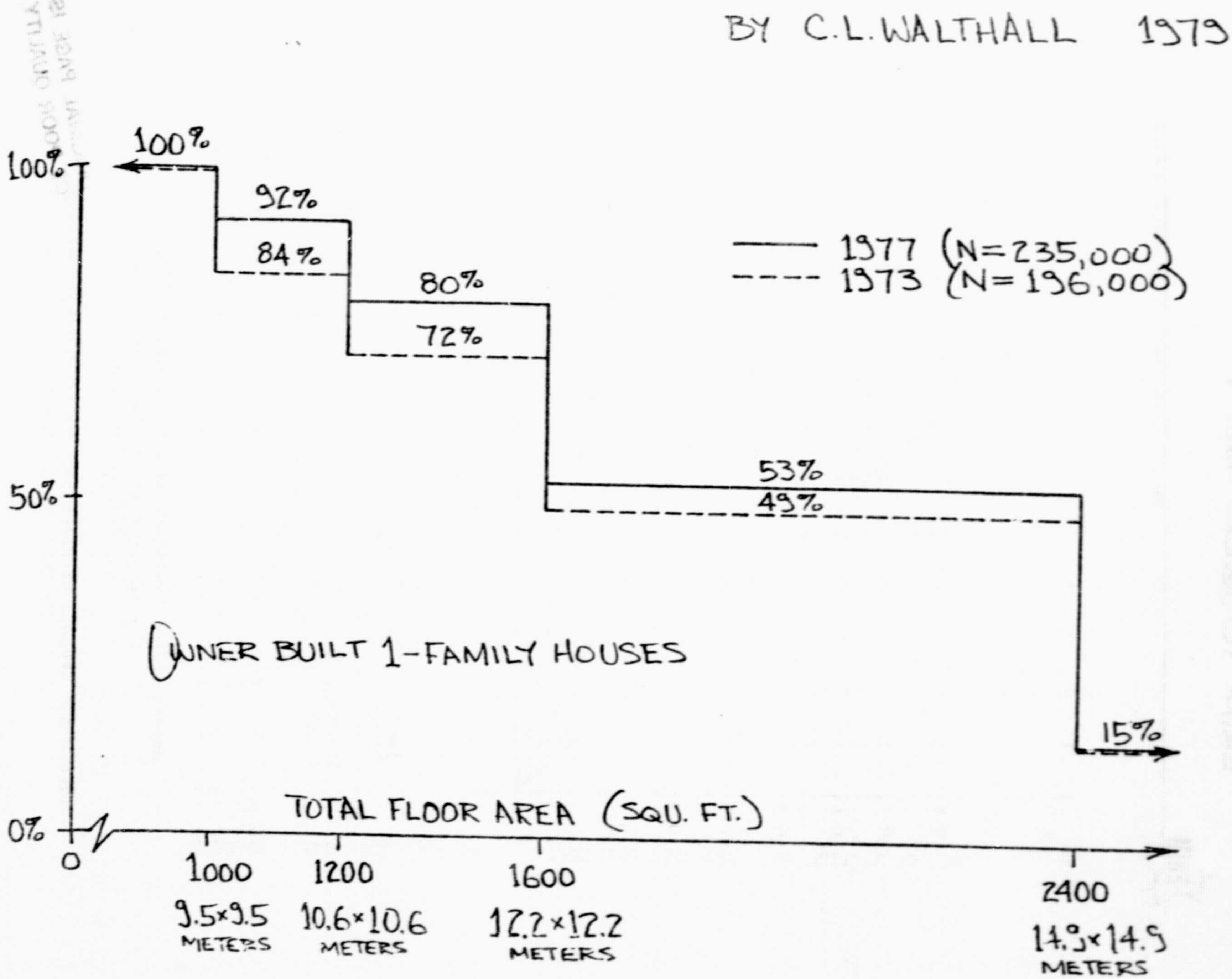
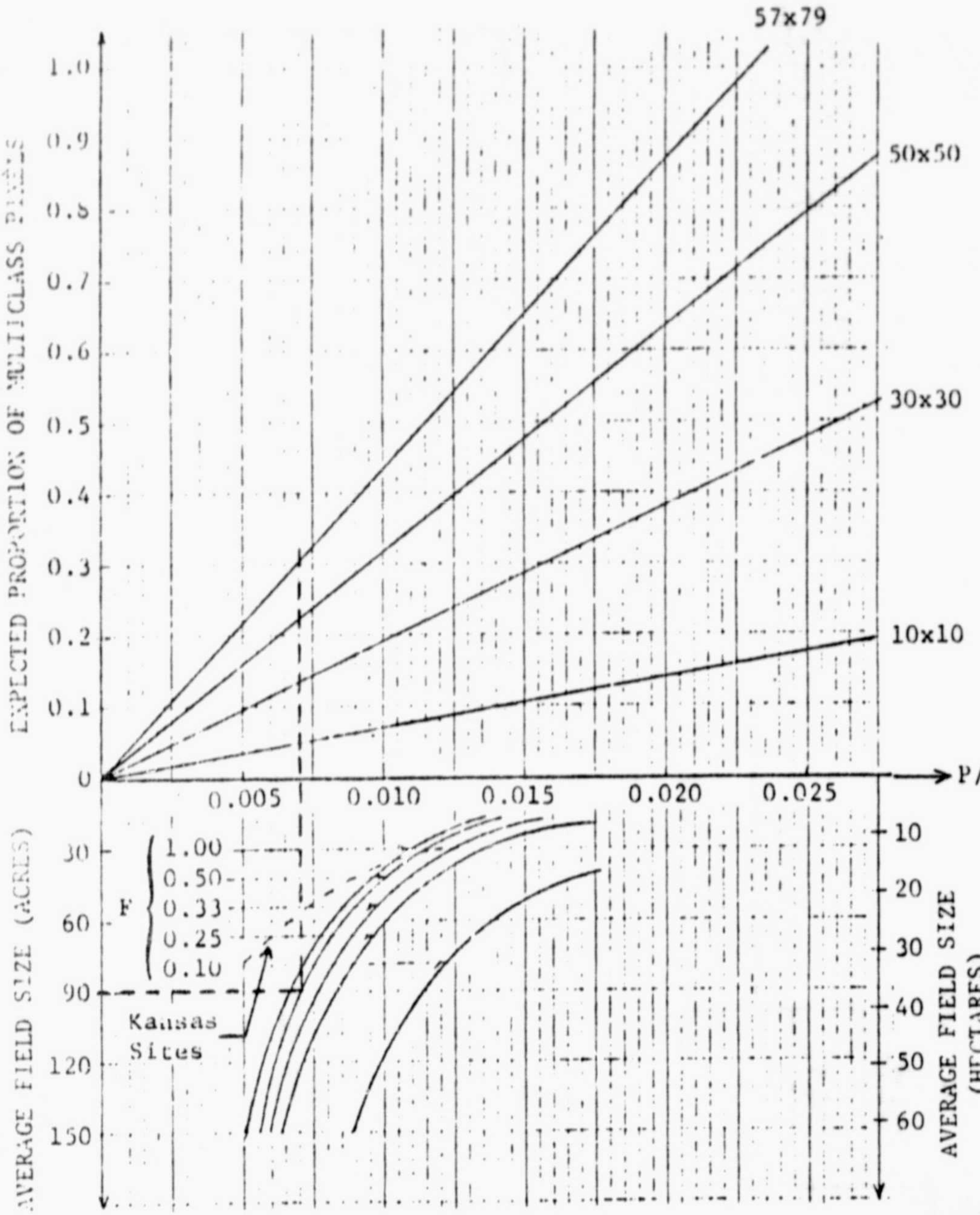

BY C.L. WALTHALL 1979
1977 (N=235,000)
1973 (N=196,000)
100%
92%
84%
80%
72%
53%
49%
15%
100%
50%
0%
OWNER BUILT 1-FAMILY HOUSES
TOTAL FLOOR AREA (SQU. FT.)
0
1000
9.5×9.5 METERS
1200
10.6×10.6 METERS
1600
12.2×12.2 METERS
2400
14.9×14.9 METERS

Figure 3.9.9

BY W.A. MALILA et al 1976
ERIM 109600-68-F



Notes: P/A = Perimeter-to-area ratio of scene.
F = Aspect ratio of rectangular fields in simulated scene.

FIGURE 8. EFFECTS OF PIXEL SIZE ON EXPECTED PROPORTION OF MULTICLASS PIXELS

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Figure 3.9.10

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POTENTIALS OF POLARIZATION

DR. ROBERT WALRAVEN

3.10

The gist of this presentation is contained in Dr. Walraven's paper entitled "Polarization Imagery" (SPIE Vol. 112, Optical Polarimetry (1977)), which is included here for reference.

POLARIZATION IMAGERY

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University of California, Davis 95616

Abstract

The polarization of reflected radiation can provide useful information which could be used in remote sensing applications to help distinguish different natural surfaces with similar spectral signatures. Yet the use of polarization has been almost completely neglected in remote sensing applications partially because of the lack of understanding of the information contained in the polarization field. In this paper, examples of the polarization of natural scenes will be presented and the information contained in the polarization field will be discussed. The imagery presented was collected by taking sets of four photographs of various natural scenes using a polarizing filter to detect the polarization field. The polarization field was analyzed by digitizing the photographs and processing the results at the Image Processing Laboratory on the Berkeley campus of the University of California.

Introduction

A beam of incoherent radiation reflected from a natural surface can be completely described at a given wavelength by the Stokes vector

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

where I, Q, U, and V are physical observables describing independent features of the electric vector. The quantity I represents the intensity of the radiation and the quantities Q, U, and V are associated with the polarization of the radiation. Traditionally, in remote sensing experiments only I is detected while Q, U, and V are neglected. However, there is useful physically independent information contained in the polarization parameters, as we will show presently.

Detection of Polarization Parameters

A simple way to detect the Stokes parameters Q and U for a natural scene is to take photographs of the scene with a standard polarizing filter in front of a camera. The intensity seen by the camera is then

$$I'(\theta) = (I + Q\cos 2\theta + U\sin 2\theta)/2, \tag{1}$$

where I, Q, and U are the Stokes parameters before passing through the polarizer, and θ is the angle of the transmission axis of the polarizer with respect to the horizontal. We took sets of four photographs of natural scenes with θ set to 0, 45, 90, and 135 degrees. The intensity recorded in each of the four photographs is, from Equation (1),

$$I'(0) = (I + Q)/2, \tag{2}$$
$$I'(45) = (I + U)/2, \tag{3}$$
$$I'(90) = (I - Q)/2, \tag{4}$$

and

$$I'(135) = (I - U)/2. \tag{5}$$

From Equations (2)-(5) it follows that

$$I = (I'(0) + I'(45) + I'(90) + I'(135))/2, \tag{6}$$
$$Q = I'(0) - I'(90), \tag{7}$$

and

$$U = I'(45) - I'(135). \tag{8}$$

When discussing polarization, it is easier to think in terms of the magnitude, P, and the phase angle, θ_o, of the polarization. Equation (1) can be rewritten in terms of P and θ_o as

$$I'(\theta) = I\ (1 + P\cos 2(\theta-\theta_o))/2. \tag{9}$$

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It is easily shown that

$$P = (Q^2 + U^2)^{1/2}/I, \quad (10)$$

and

$$\theta_o = \tan^{-1}(U/Q). \quad (11)$$

The Stokes parameter V has been ignored. For natural scenes it is so small that it cannot even be measured by simple means.

Production of Imagery

Each photograph in a set of four was scanned and digitized as a 512 x 512 pixel image. The digitization precision was 8 bits per pixel (1 part in 256). The digitized images were not corrected for nonlinearities in the response of the film as a function of intensity. Equations (6), (7), (8), (10), and (11) were used to calculate the intensity and polarization in each pixel of the image. For simplicity, the quantity

$$POL = I(1-P) \quad (12)$$

was calculated instead of P. The resulting digitized images of I, POL, and θ_o were displayed using a high-resolution camera system. The results for three different natural scenes are shown in Figures (1)-(3), (4)-(6), and (7)-(9), respectively. (Note: The streaks in Figure 2 were caused by an error in coating the final prints and are not a feature of the actual image.)

Discussion

Major features such as buildings, trees, posts, sky, and roads are easily distinguishable in images of I, POL, and θ_o. Any one of these three parameters could be used to detect the gross features in a scene. The images of POL and θ_o, however, are clearly different from the images of I. These differences can provide new and useful information about the features in the scene.

Scene 1

Figure 1. Scene 1, I.

Figure 2. Scene 1, POL.

Figure 3. Scene 1, θ_o.

The major features in this scene are 1) a concrete building with many windows, 2) a light pole with a sign on it, 3) low ground cover in the center of the scene, 4) mowed grass in front of the building, 5) an asphalt road running through the middle of the scene, and 6) an asphalt path with some water on it in the foreground. The windows of the building, the asphalt road, and the puddle of water have large polarizations, and show up clearly as dark areas in the POL image. (The windows in the lower middle part of the building are different because they are reflecting light from ground features rather than skylight.) The alternating horizontal bands in the window areas of the θ_o image are the result of poor signal-to-noise in these areas. The lawn in front of the building contains two types of grass. There is no indication of this fact in the I image, but it shows up clearly in the θ_o image. Differences in the ground cover in the middle of the scene also show up in the θ_o image.

Scene 2

Figure 4. Scene 2, I.

Figure 5. Scene 2, POL.

Figure 6. Scene 2, θ_o.

This scene was photographed in the same vicinity as scene 1, but looking in a different direction. The same puddle of water shows in the foreground. The two light roofs in the I image appear to be quite different in the POL and θ_o images. Again, the road and water puddle show up clearly in the POL image and the θ_o image shows some variations in the ground cover which are not apparent in the I image.

Scene 3

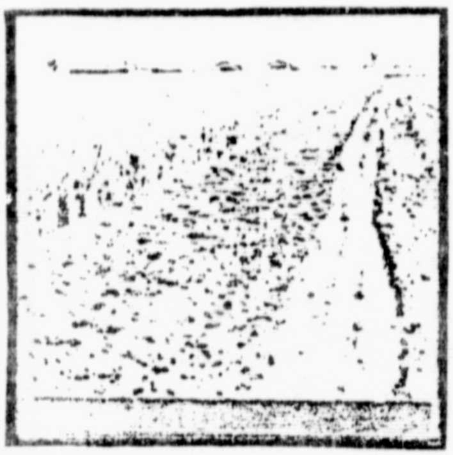

Figure 7. Scene 3, I.

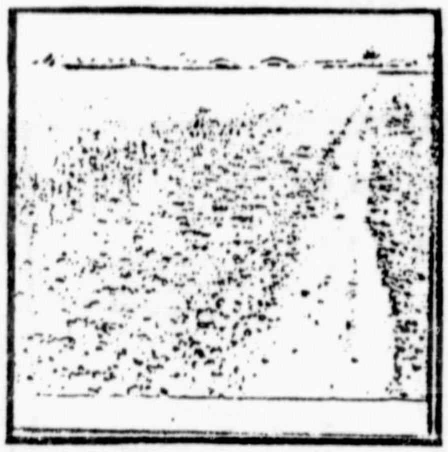

Figure 8. Scene 3, POL.

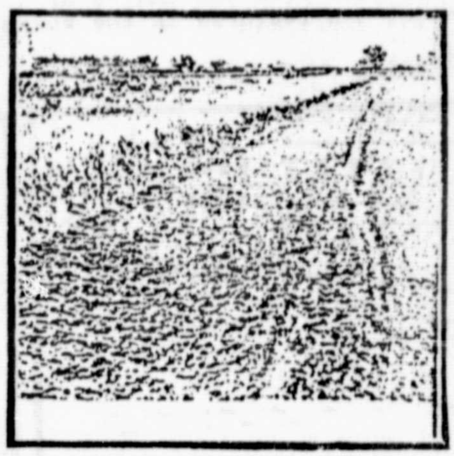

Figure 9. Scene 3, θ_o.

This scene shows a wheat field on the left and a dirt road on the right. There are some buildings, trees, and a water tower on the horizon. Details of the buildings show more clearly in the POL image than they do in the I image, but the water tower and a stake in the middle of the scene seem to disappear in the POL image. The θ_o image shows a bright area along the edge of the field. This feature indicates wheat that is more stressed (because it is on the edge of the field) and more mature (because of heat radiated from the dirt road).

COLOR IMAGERY

Polarization is a vector quantity, it has magnitude and direction. Color, also, can be thought of as a vector quantity, it has hue (color) and saturation (depth of color). It is rather straightforward, then, to create an image from the magnitude and phase angle of the polarization such that there is a one-to-one correspondence between particular colors and particular states of polarization. Such a color image was created from POL and θ_o for scene 3. Figure 10 is a black-and-white picture of one of the three primary colors that made up that image. Notice that the stressed area of the wheat field and the water tower on the horizon stand out strongly. The intensity I could also be added to a color image displaying the polarization by using it to set the gray scale in the scene.

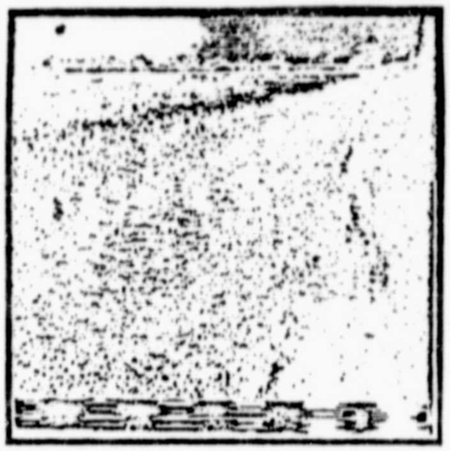

Figure 10. Black-and-white image of one of the primary colors of a color image of polarization.

Conclusions

There is physically independent information that is contained in the amplitude and phase angle of the polarization in natural scenes that can be used in conjunction with intensity information to better distinguish similar surfaces. The amplitude and phase angle of the polarization are quite easily detectable by standard photographic methods, and can be displayed by standard image processing techniques. False color images can be created from the polarization information to emphasize particular features of interest in the scene.

Acknowledgments

The author wishes to thank the personnel at the Image Processing Laboratories on the Davis and Berkeley campuses of the University of California for their patience and assistance in helping to produce the images in this paper.

TEMPORAL RESOLUTION CONSIDERATIONS
DR. ARCHIBALD PARK

3.11

The MRS will be capable of providing increased temporal coverage because of its pointing capability. This increased coverage is extremely important for applications where the target changes significantly over relatively short periods of time. Agricultural crops are such a target. During the growing season the reflectance and textural characteristics of agricultural crops may change rapidly. This is illustrated in Figure 3.11.1 which shows the crop calendar for the MESA Test site. Crop characteristics change as the plant grows both because of inherent changes in the color, size and shape of the plant and because of increasing foliar canopy which covers the bare soil. More drastic changes occur when the crops are harvested.

The calendar varies for different crops and different areas. For example, the time interval between distinct growth stages of hybrid corn in central Iowa is about 14 days, suggesting that remote monitoring of this corn crop would require periodic coverage with a return time of about 14 days (Figure 3.11.2) This period may vary within a season or from year to year depending on rainfall and temperature. Figure 3.11.3 shows the crop calendar for corn in terms of growing degree days. Adding to this the fact that the growing stage may vary by as much as 30 days over an entire state, the need for frequent coverage becomes clear.

Temporal coverage is only important if we can determine the stage of growth from the remote measurements. The stage of growth is itself a very important piece of information but growth characteristics are also important in identifying and quantifying stress conditions. To illustrate the capability of observing growth stage characteristics by remote sensing, we will consider data collected over four crops in 1977. The reflectance of these crops (in the TM bands) for several dates throughout the growing season is presented in Figure 3.11.4. The first column (4/21/77) is the reflectance of bare soil. The second column (5/10/77) shows a distinct increase in the reflectance corresponding to the emergence of plant material, but the increase in this case is too much too soon (particularly in the IR) primarily due to atmospheric path radiance. We have found that a simple, but effective method of correcting for the atmospheric effect for our purposes is to normalize the readings to

MESA TEST SITE
CROP CALENDAR - 1969 SEQUENTIAL COLOR

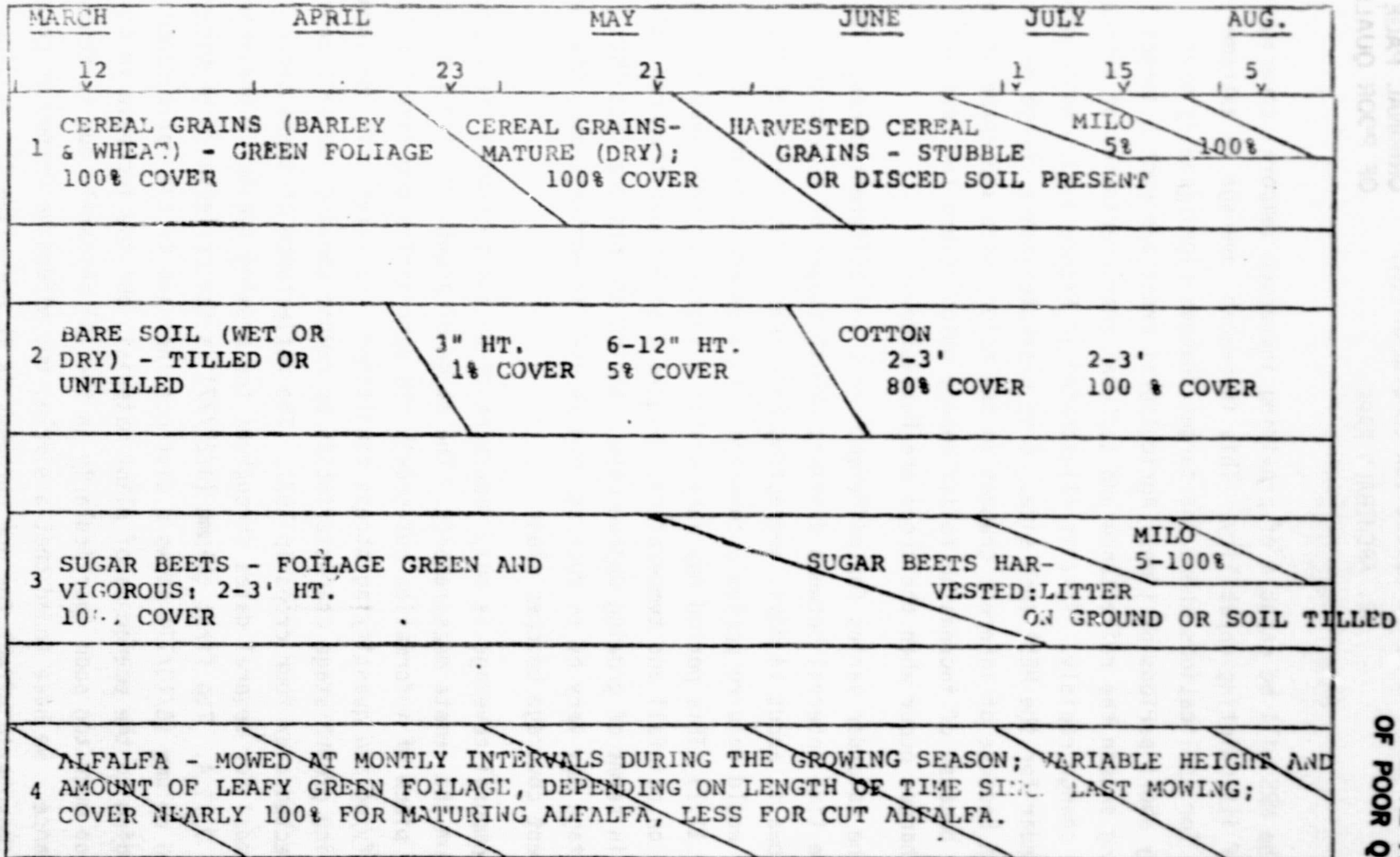

Figure 1.

Figure 3.11.1

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Table 1. Average Dates and Days from Emergence for the Different Stages of Growth of Corn[a]

GROWTH STAGE	DATE	DAYS[b]	IDENTIFYING CHARACTERISTICS FOR FIELD USE
0	May 24	0	Plant emergence. Tip of coleoptile of plant visible at soil surface.
1	Jun 8	14	Collar of 4th leaf visible.
2	Jun 22	28	Collar of 8th leaf visible. Leaves 1 and 2 may be dead.
3	Jul 6	42	Collar of 12th leaf visible. Leaves 3 and 4 may be dead.
4	Jul 20	56	Collar of 15th leaf visible. Tips of many tassels visible. Leaves 5 and 6 may be dead.
5	Jul 30	66	75% of plants have silks visible. Pollen shedding.
6	Aug 11	78	12 days after 75% silked. Kernels in "blister" stage.
7	Aug 23	90	24 days after 75% silked. Very late "roasting ear" stage.
8	Sep 4	102	36 days after 75% silked. Early "dent" stage.
9	Sep 16	114	48 days after 75% silked. Full "dent" stage.
10	Sep 28	126	60 days after 75% silked. Grain physiologically mature.

a) Average for adapted hybrids in central Iowa. Appropriate modifications should be employed for other bybrids and other areas. Planting date assumed to be May 15.

b) From emergence.

Figure 3.11.2

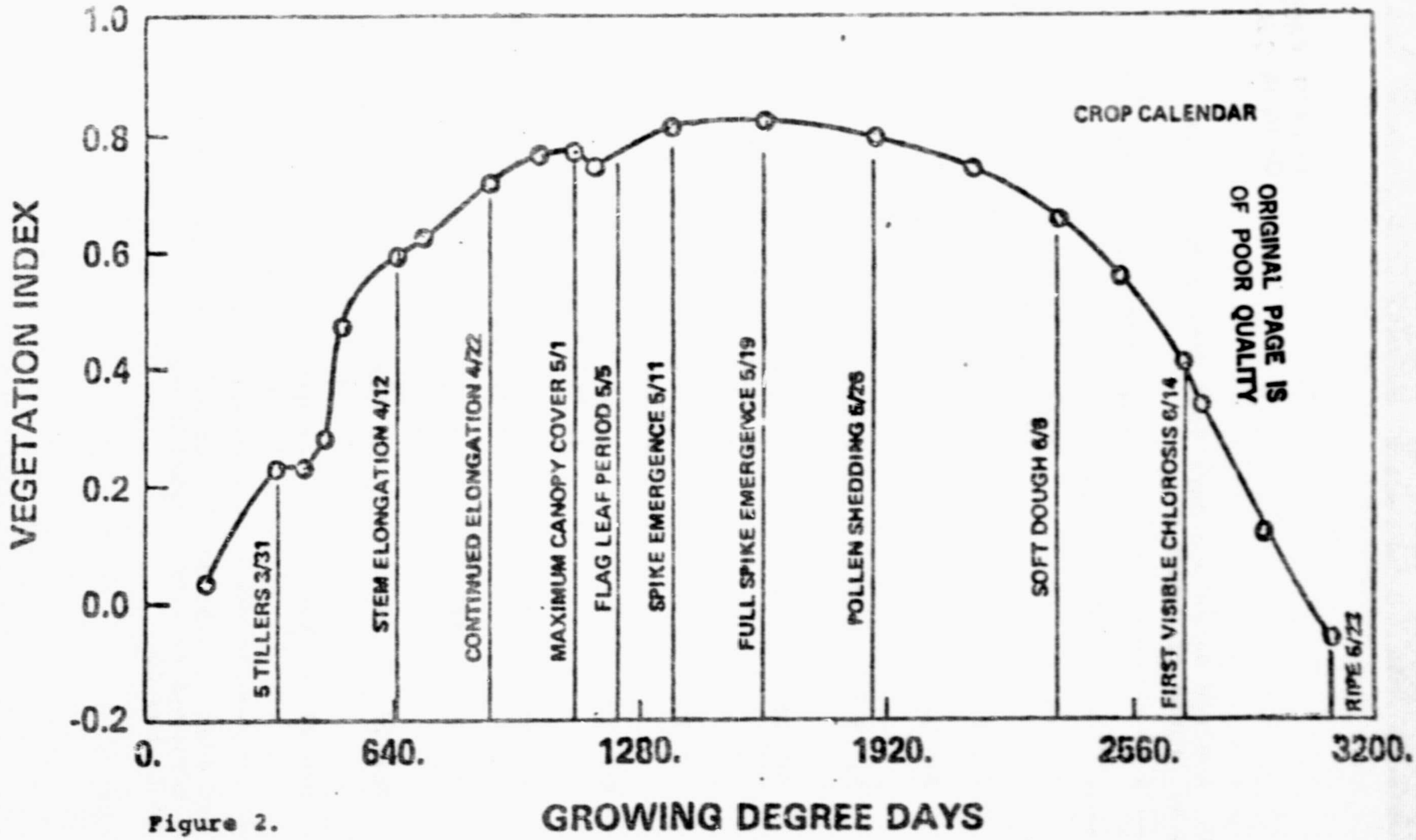

Figure 2.

Figure 3.11.3

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Table

Mean of Means - Bidirectional Reflectance Versus Time and Wavelength Over Fields of a Class. (Hand County)

WAVELENGTH INTERVAL	DATES OF MEASUREMENT					
Winter Wheat	4/21/77	5/10/77	6/1/77	6/16/77	7/7/77	7/27/77
.45 - .52	3.61	5.85	3.18	2.79	6.49	6.58
.52 - .60	4.51	7.97	5.03	4.22	8.86	9.00
.63 - .69	6.15	10.18	6.67	5.69	12.66	12.75
.76 - .90	9.97	23.55	27.63	23.25	21.48	19.92
1.55 - 1.75	18.58	27.14	17.33	15.29	28.67	28.04
2.08 - 2.35	13.07	19.37	9.58	8.48	20.37	20.71
Corn						
.45 - .52	5.00	6.66	6.11	5.65	5.20	4.79
.52 - .60	6.32	8.80	7.76	7.49	7.21	6.63
.63 - .69	8.23	11.31	10.49	9.73	9.50	8.77
.76 - .90	12.87	23.23	16.29	13.10	24.08	21.27
1.55 - 1.75	21.65	28.52	29.46	29.41	28.52	25.25
2.08 - 2.35	14.93	21.69	24.68	24.99	20.62	18.23
Spring Wheat - 1						
.45 - .52	2.72	6.91	3.28	2.33	4.33	8.12
.52 - .60	3.35	8.76	5.17	3.75	6.64	11.36
.63 - .69	4.68	11.33	6.73	4.90	10.05	16.29
.76 - .90	7.21	18.62	27.73	26.63	23.69	23.05
1.55 - 1.75	16.42	31.72	19.41	13.59	21.31	31.01
2.08 - 2.35	11.86	26.10	10.53	6.20	13.03	21.87
Oats - 1						
.45 - .52	2.1	6.16	3.17	2.22	5.30	6.85
.52 - .60	3.32	7.98	4.74	3.65	7.66	9.48
.63 - .69	4.60	10.28	6.35	4.83	11.36	13.58
.76 - .90	7.05	19.01	23.22	24.66	21.21	20.75
1.55 - 1.75	15.31	27.94	17.51	12.34	24.78	28.42
2.08 - 2.35	10.94	21.83	10.18	5.92	17.36	20.84

Figure 3.11.4

the reflectance in the blue, i.e., to divide all the reflectance values by the reflectance in the blue. Figure 3.11.5 shows the corrected values for the 1977 data. These values are much more reasonable; the increased reflectance is only apparent in TM band 4 (.76 -.90μ) for winter wheat and corn.

Using these corrected values we have found a means of indicating the presence of bare soil. This is illustrated in Figures 3.11.6 through 3-11.14. (Figures 3.11.6 through 3.11.9 show the data presented in Figures 3.11.4 and 3.11.5.) In each case three ratios are plotted- 4/3, 4/5, and 6/5. For visual clarity, whenever these ratios are less than one the negative inverse of the ratio is plotted. Whenever the ratio of band 4 to band 5 is less than one, but greater than the ratio of band 6 to band 5, the target is bare soil. In the graphs this occurs when the line for 4/5 falls below the line for 6/5 and both are negative.

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Mean of Means - Normalized (Hand County)

WAVELENGTH INTERVAL	DATES OF MEASUREMENT					
Winter Wheat	4/21/77	5/10/77	6/1/77	6/16/77	7/7/77	7/27/77
.45 - .52	1.00	1.00	1.00	1.00	1.00	1.00
.52 - .60	1.25	1.36	1.58	1.51	1.37	1.37
.63 - .69	1.70	1.74	2.10	2.04	1.95	1.94
.76 - .90	2.76	4.03	8.69	8.33	3.31	3.03
1.55 - 1.75	5.15	4.64	5.45	5.48	4.42	4.26
2.08 - 2.35	3.62	3.31	3.01	3.04	3.14	3.15
Corn						
.45 - .52	1.00	1.00	1.00	1.00	1.00	1.00
.52 - .60	1.26	1.32	1.27	1.33	1.39	1.38
.63 - .69	1.65	1.70	1.72	1.72	1.83	1.83
.76 - .90	2.57	3.49	2.67	2.32	4.63	4.44
1.55 - 1.75	4.33	4.28	4.82	5.21	5.48	5.27
2.08 - 2.35	2.99	3.26	4.04	4.42	3.97	3.81
Spring Wheat						
.45 - .52	1.00	1.00	1.00	1.00	1.00	1.00
.52 - .60	1.23	1.27	1.58	1.61	1.53	1.40
.63 - .69	1.72	1.64	2.05	2.10	2.32	2.01
.76 - .90	2.65	2.69	8.45	11.43	5.47	2.84
1.55 - 1.75	6.04	4.59	5.91	5.83	4.92	3.82
2.08 - 2.35	4.36	3.78	3.21	2.66	3.01	[illegible].89
Oats						
.45 - .52	1.00	1.00	1.00	1.00	1.00	1.00
.52 - .60	1.58	1.30	1.50	1.64	1.45	1.33
.63 - .69	2.19	1.67	2.00	2.18	2.14	1.98
.76 - .90	3.36	3.09	7.32	11.11	4.00	3.03
1.55 - 1.75	7.29	4.54	5.52	5.56	4.68	4.15
2.08 - 2.35	5.16	3.54	3.21	2.67	3.28	3.04

Figure 3.11.5

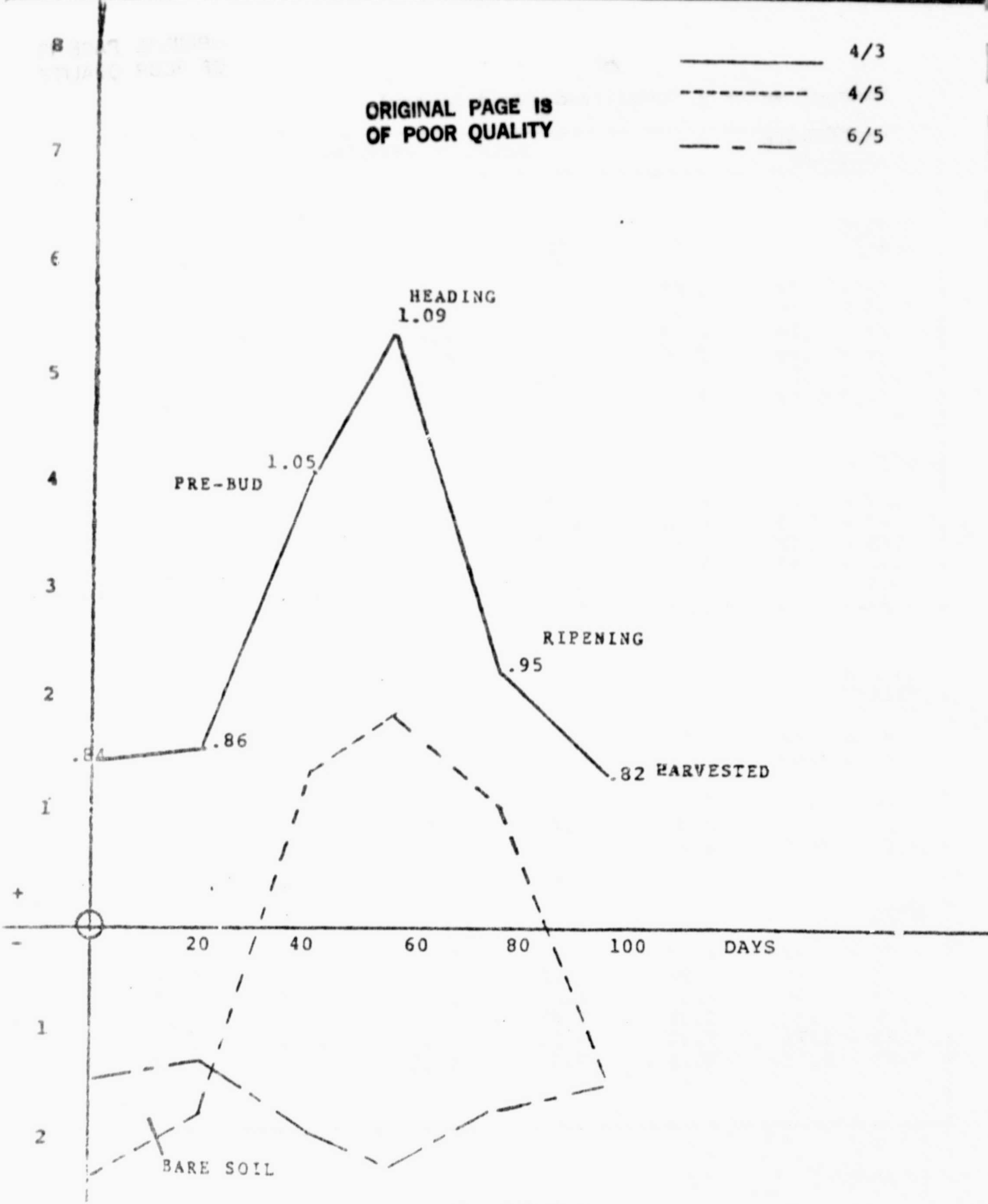

Figure 3.11.6

SPRING WHEAT
(HAND COUNTY)

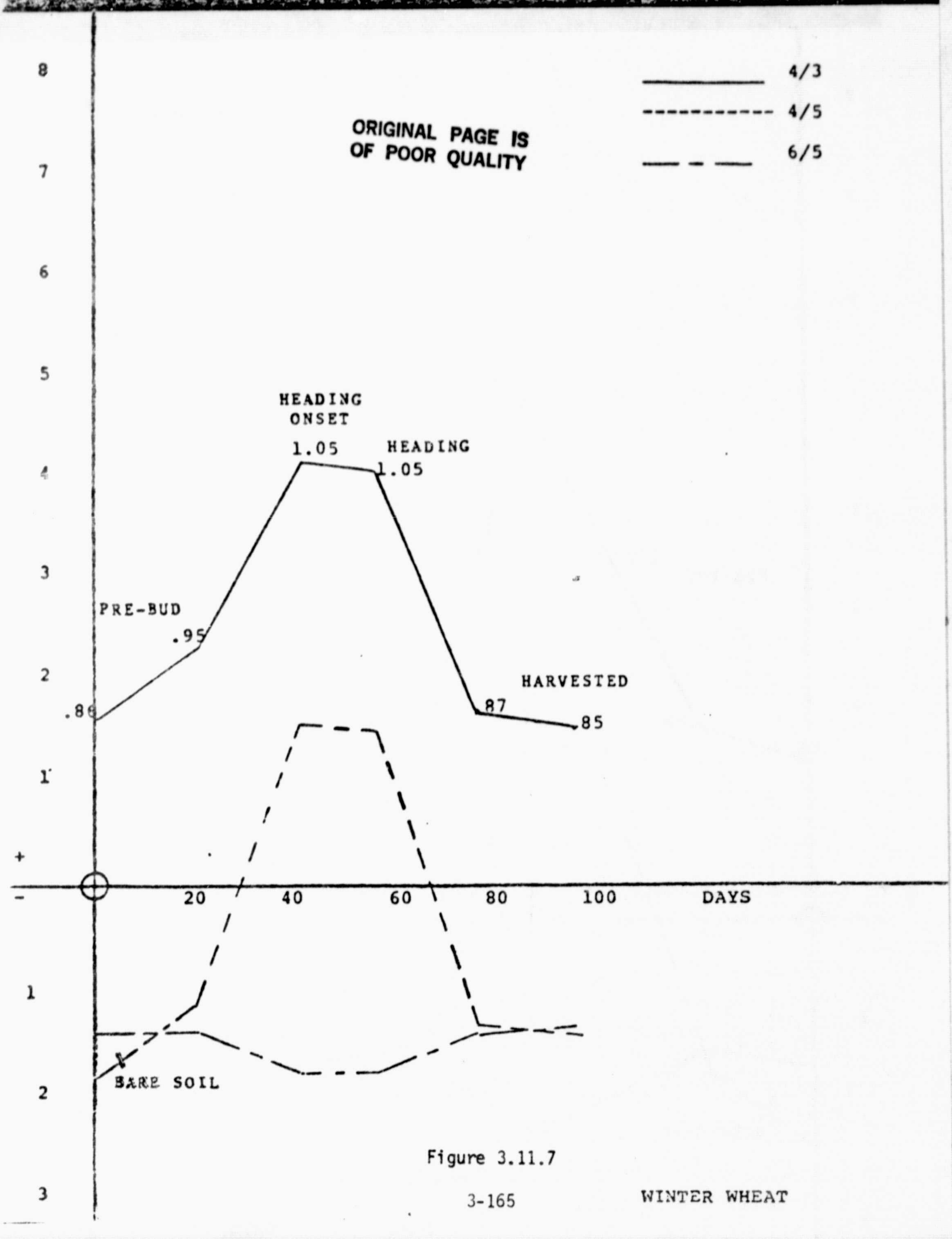

Figure 3.11.7

WINTER WHEAT

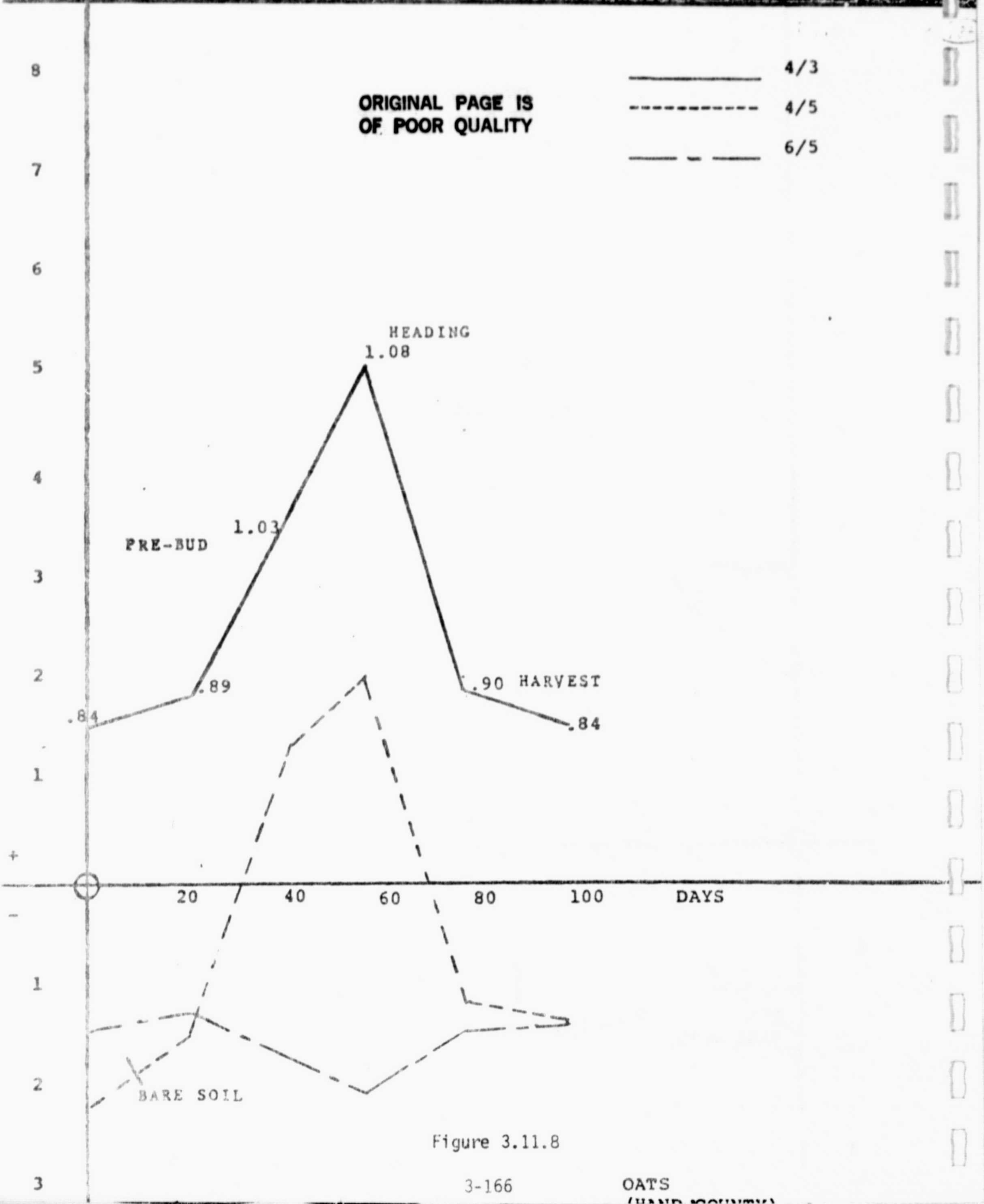
4/3
4/5
6/5
HEADING
1.08
1.03
PRE-BUD
.84
.89
.90
HARVEST
.84
BARE SOIL
8
7
6
5
4
3
2
1
+
−
1
2
3
20
40
60
80
100
DAYS
OATS

Figure 3.11.8

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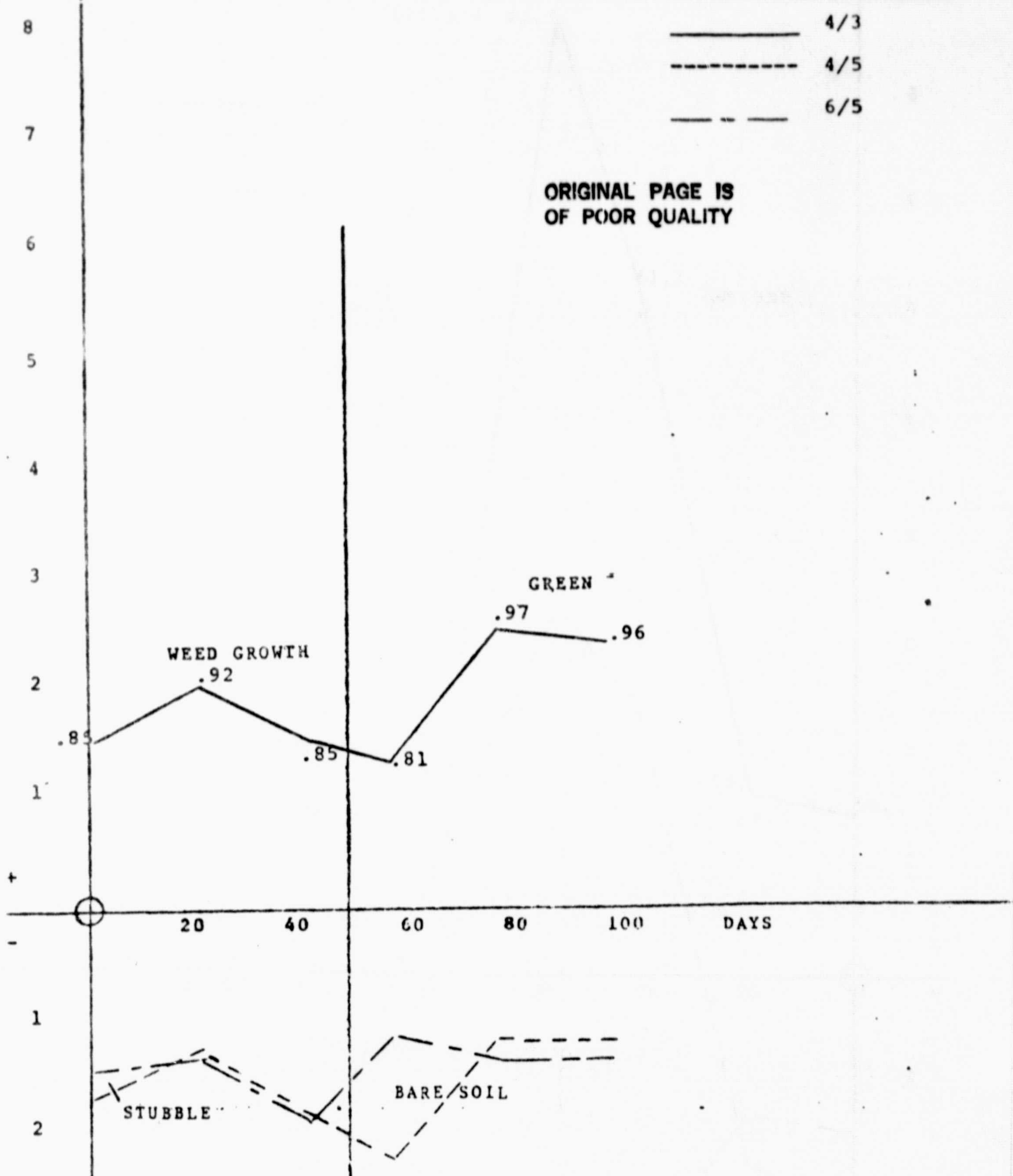

Figure 3.11.9

CORN
(HAND COUNTY)

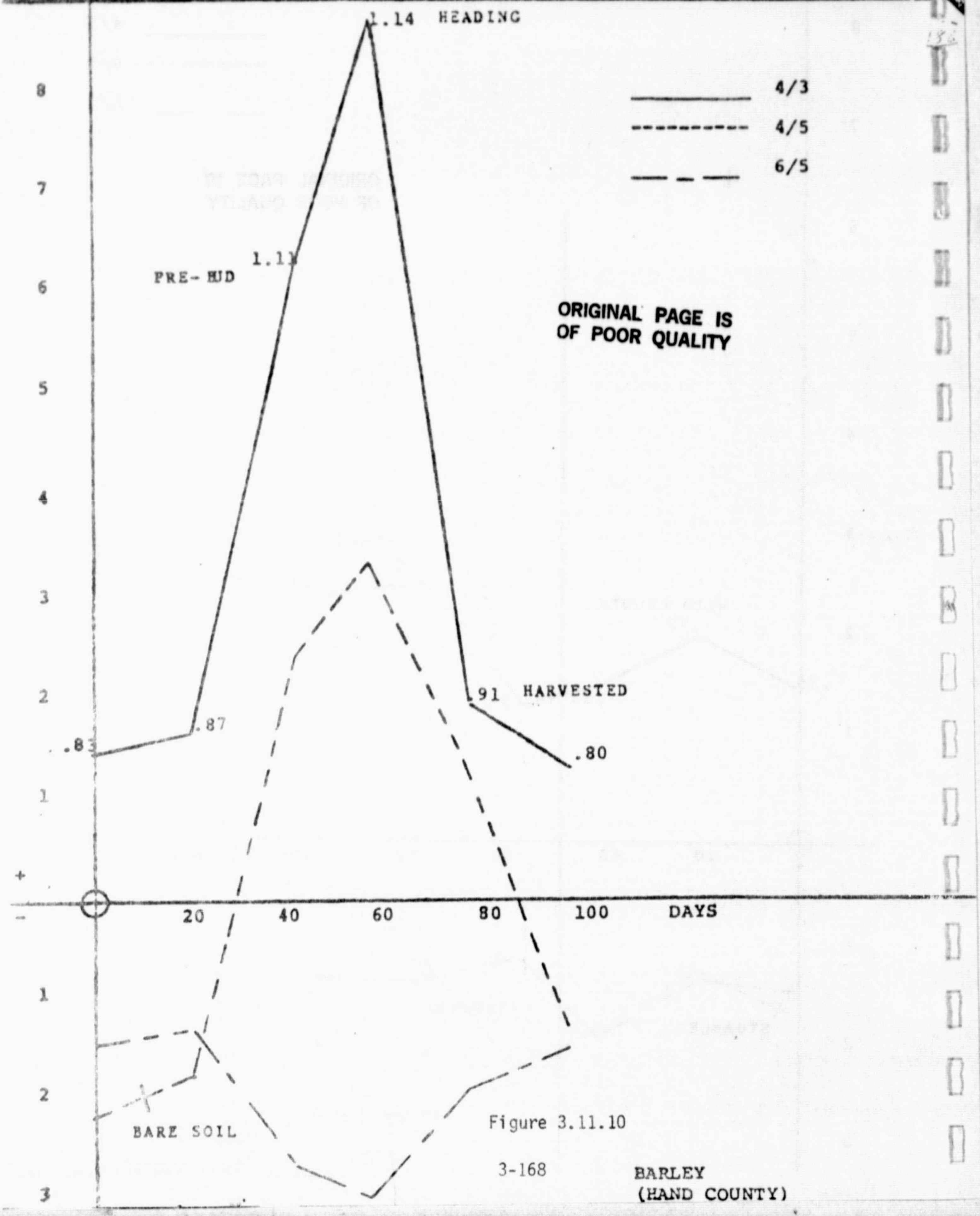

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Figure 3.11.10

BARLEY (HAND COUNTY)

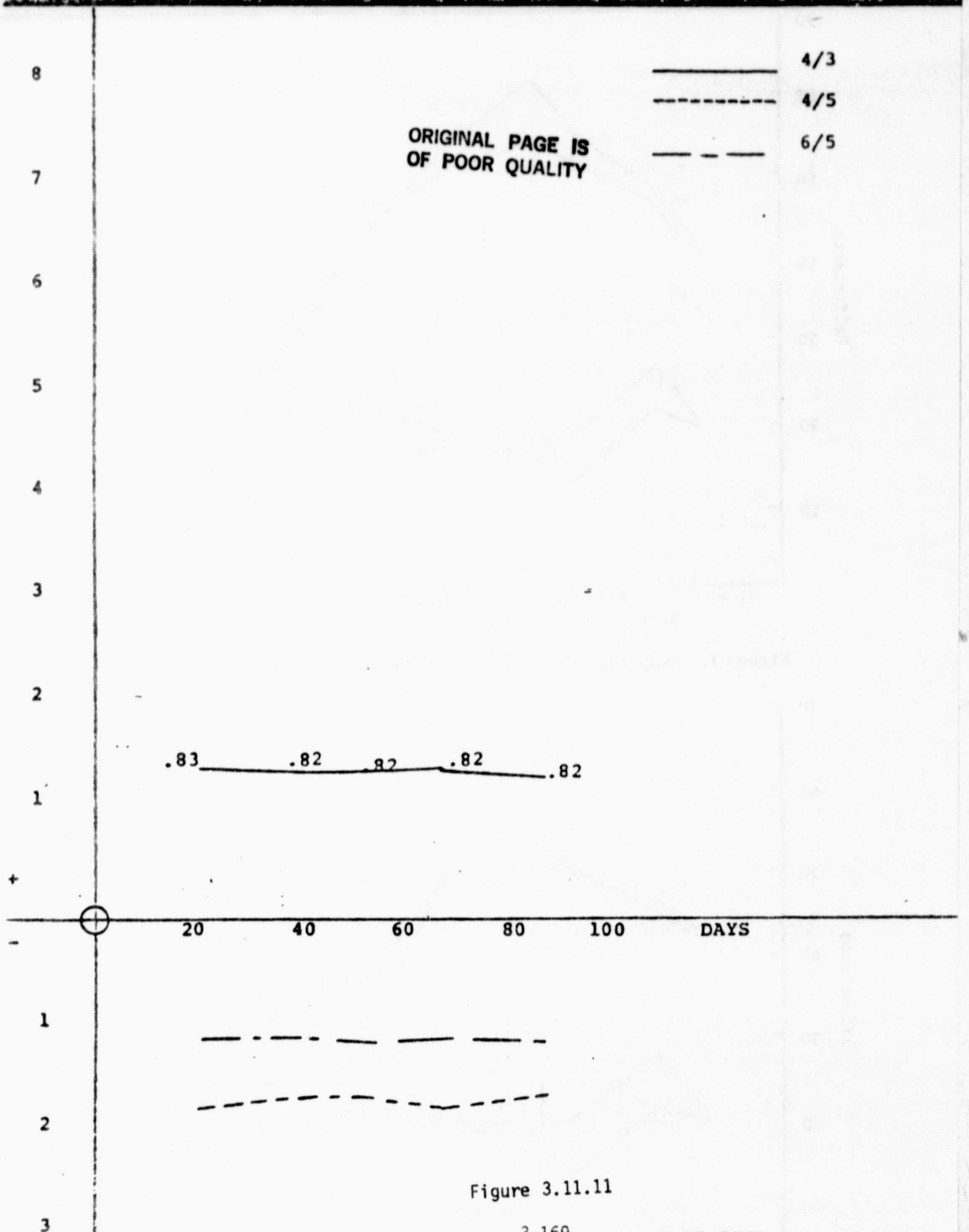

Figure 3.11.11

BARE SOIL

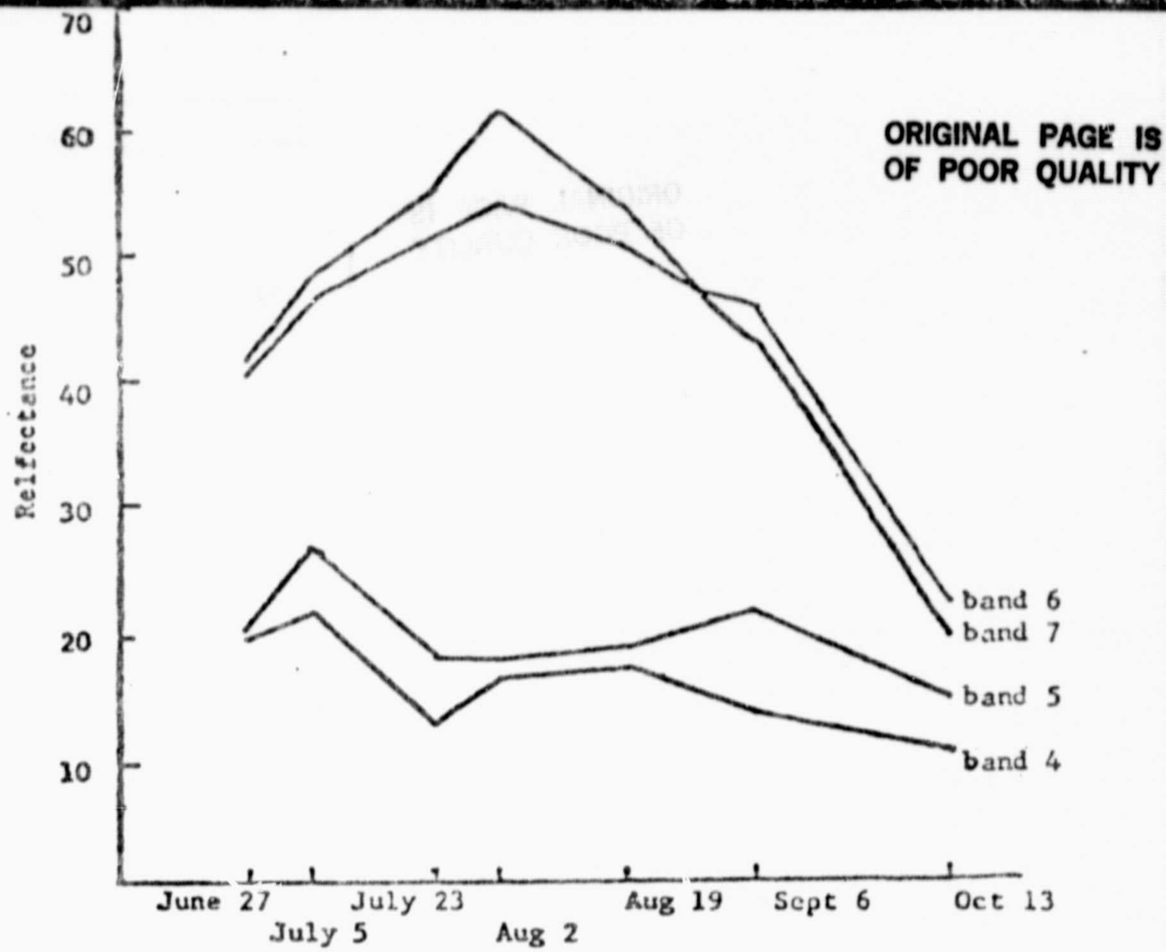

Figure 3. Temporal Spectral Profile for Normal Iowa Corn, 1976

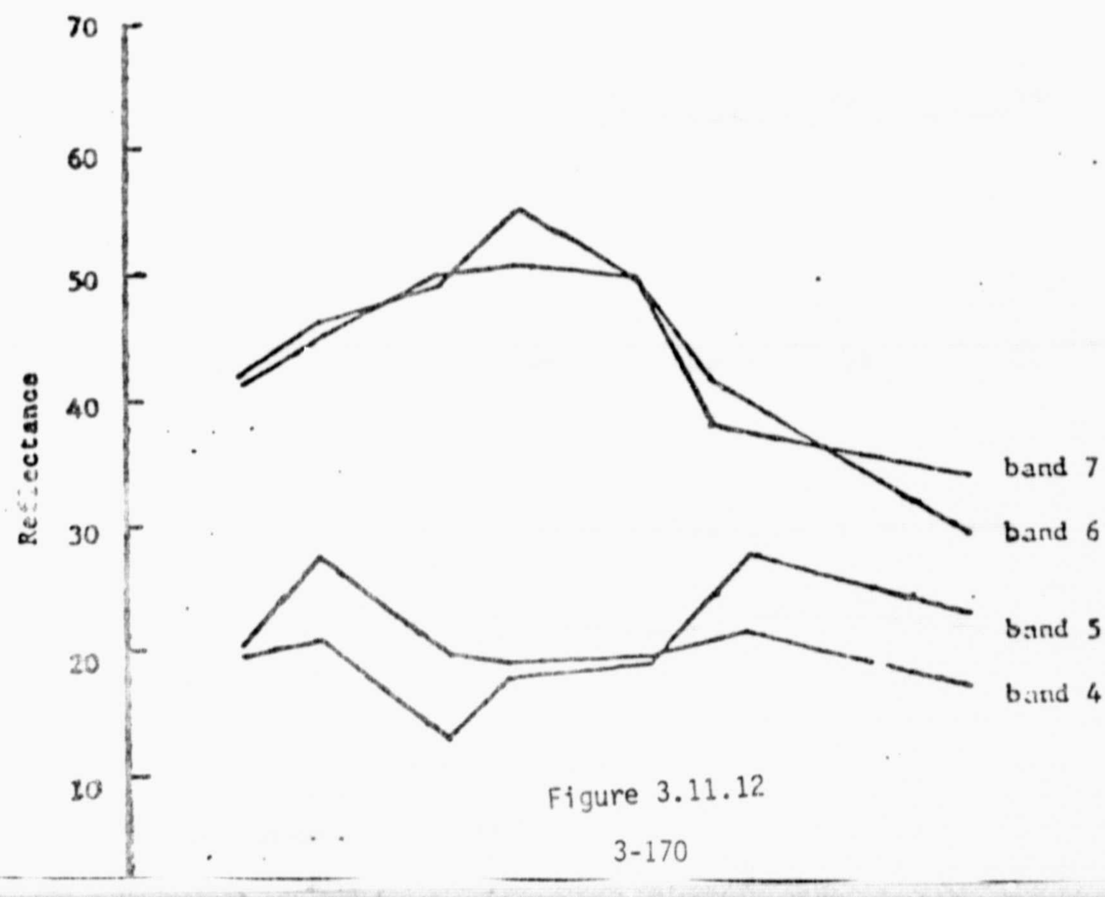

Figure 3.11.12

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Table 7

CORRECTED MSS 7/4 and 5/4 VALUES.

		5/20/76	6/25/76	7/04/76	7/22/76	8/09/76
FIELD - FALLOW	MSS 4/4	1.00	1.00	1.00	1.00	1.00
	MSS 5/4	1.01	.99	1.34	1.34	1.28
	MSS 7/4	.90	.95	1.33	1.30	1.10
	P 7/4 MAX	.68	.71	1.00	.98	.86
	MSS 7/5	.89	.96	.99	.97	.86
	P 7/5 MAX	.90	.97	1.00	.98	.87
	MSS 5/4-MSS 7/5	+.12	+.03	+.35	+.36	+.42
	MSS 7/4-MSS 7/5	+.01	-.01	+.34	+.33	+.24
FIELD 679	$T_2 \cdots\cdots T_6$	9	45	54	72	90
PLANTING	ADJ MSS 5/4	.84	.61	.66	.79	1.06
DATE	ADJ MSS 7/4	.80	2.00	3.17	2.13	1.33
	ADJ P 7/4 MAX	.25	.63	1.00	.67	.42
T_1 = 5/11	MSS 7/5	.84	3.09	3.46	2.15	1.06
YIELD 18	P 7/5 MAX	.24	.89	1.00	.62	.31
FIELD 478	$T_2 \cdots\cdots T_6$	15	51	59	77	95
PLANTING	ADJ MSS 5/4	.85	.65	.69	.72	1.03
DATE	ADJ MSS 7/4	.84	1.76	2.64	2.22	1.45
	ADJ P 7/4 MAX	.32	.67	1.00	.84	.55
T_1 = 5/5	MSS 7/5	.87	2.57	2.85	2.37	1.14
YIELD 25.4	P 7/5 MAX	.31	.90	1.00	.83	.40
FIELD 235	$T_2 \cdots\cdots T_6$	0	34	43	61	79
PLANTING	ADJ MSS 5/4	.88	.63	.65	.70	1.06
DATE	ADJ MSS 7/4	.79	2.02	3.16	2.18	1.51
	ADJ P 7/4 MAX	.25	.64	1.00	.69	.48
T_1 = 5/22	MSS 7/5	.80	3.05	3.52	2.38	1.18
YIELD 19	P 7/5 MAX	.23	.87	1.00	.68	.34

YIELD REGRESSION WITH P 7/4 MAX FOR MAY 20

$$Y = .01\ x + .07$$

$$R = .83$$

Figure 3.11.13

Table 6 (Continued)

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MSS WILLIAMS COUNTY, NORTH DAKOTA

		5/20/76	6/25/76	7/04/76	7/22/76	8/09/76
FIELD 2[illegible]3	MSS 4/4	1.00	1.00	1.00	1.00	1.00
	MSS 5/4	.97	.65	.98	1.09	1.54
	MSS 6/4	.96	1.94	3.16	2.42	2.03
	MSS 7/4	.80	2.12	3.43	2.53	1.75
	MSS 7/5	.83	3.27	3.51	2.32	1.14
FIELD 334	MSS 4/4	1.00	1.00	1.00	1.00	1.00
	MSS 5/4	.95	.68	.99	.96	1.44
	MSS 6/4	.97	1.50	2.90	2.59	2.05
	MSS 7/4	.83	1.47	3.12	2.82	1.75
	MSS 7/5	.87	2.15	3.14	2.94	1.22
FIELD 679	MSS 4/4	1.00	1.00	1.00	1.00	1.00
	MSS 5/4	.96	.64	1.01	1.15	1.48
	MSS 6/4	.95	1.92	3.24	2.39	1.87
	MSS 7/4	.81	1.99	3.51	2.46	1.57
	MSS 7/5	.84	3.09	3.46	2.15	1.06
FIELD 478	MSS 4/4	1.00	1.00	1.00	1.00	1.00
	MSS 5/4	.97	.68	1.04	1.08	1.45
	MSS 6/4	.98	1.72	2.85	2.46	1.96
	MSS 7/4	.85	1.75	2.98	2.55	1.69
	MSS 7/5	.87	2.57	2.85	2.37	1.14
FIELD 235	MSS 4/4	1.00	1.00	1.00	1.00	1.00
	MSS 5/4	1.00	.66	1.00	1.06	1.48
	MSS 6/4	1.00	1.93	3.18	2.30	1.97
	MSS 7/4	.80	2.01	3.50	2.51	1.75
	MSS 7/5	.80	3.05	3.52	2.38	1.18
FIELD - FALLOW	MSS 4/4	1.00	1.00	1.00	1.00	1.00
	MSS 5/4	1.01	.99	1.34	1.34	1.28
	MSS 6/4	1.05	1.09	1.56	1.51	1.37
	MSS 7/4	.90	.95	1.33	1.30	1.10
	MSS 7/5	.89	.96	.99	.97	.86

Figure 3.11.14

APPENDIX A

MULTISPECTRAL RESOURCE SAMPLER:
AN EXPERIMENTAL SATELLITE SENSOR FOR THE MID 1980's

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PROCEEDINGS SPIE TECHNICAL SYMPOSIUM, HUNTSVILLE, AL

MAY 22-24, 1979, Vol. 183

MULTISPECTRAL RESOURCE SAMPLER: AN EXPERIMENTAL SATELLITE SENSOR FOR THE MID-1980'S

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Abstract

An experimental pushbroom scan sensor, called the Multispectral Resource Sampler (MRS), is being developed by NASA for an earth orbiting spacecraft flight in the mid-1980's. This sensor will provide new and unique earth survey research capabilities beyond those possible with current sensor systems, and is designed with flexibility to provide a research facility for a number of preselected experiments. The sensor will have a ground resolution (IFOV) of 15 meters over a swath width of 15 kilometers, in four bands, or 30 kilometers in two bands. A data rate limitation of 15 megabits/second controls the permitted swath width. Each of the four arrays will have five separate spectral filters that will be selectable by command while in orbit. The basic sensor uses four 2000 element detector arrays in the focal plane of a 70 cm focal length (F/3.5) telescope. The four arrays are aligned on a common focal surface; thus no beamsplitters are required. This causes a spatial separation on the ground which requires computer processing to register the bands. A 2.2 ms dwell time of the pushbroom array allows bandwidths as narrow as 20 nanometers over the spectral range from 0.35 to 1.0 micrometers. Response in each band will be quantized into eight bits. The MRS can be pointed at $\pm$ 40° in the across track direction and $\pm$ 55° in the along track direction. Along track pointing permits stereo coverage at variable base/height ratios and atmospheric correction experiments, while across track pointing will provide repeat coverage, from a Landsat-type orbit, of every 1 to 3 days. A number of significant experiments which could be performed with the MRS include experiments in crop discrimination and status, rock discrimination, geobotanical mineral exploration, land use classification and forestry.

Introduction

Electro-mechanical scanners have inherent difficulties providing high resolution remote sensing systems. In 1972, Landsat 1 was launched with the Multispectral Scanner (MSS) as one of its complement of sensors. The MSS provides a 79 meter footprint at the nadir, and represents the basic performance standard against which all following sensor systems will be compared. In fact, the MSS has generated a large constituency that demands the continued supply of its basic data products; images and computer compatible tapes. These products are becoming an archival data base, and have prompted NASA to launch the MSS on each of Landsat 2 & 3. Landsat D (4 after launch) will carry yet another MSS, in addition to the next generation electro-mechanical scanner named the Thematic Mapper (TM). The TM provides 30 meter footprints in six bands from the visible to 2.4 μm infrared (IR) and a 120 meter footprint in the 10 μm to 12 μm thermal

IR. The TM represents a very significant jump in performance over the MSS, but when it is launched in 1982, a decade will have passed in order to make possible this jump in performance. With the launch of the 30 meter TM, electro-mechanical (E-M) scanners will have reached their zenith.

Recognizing the limits of E-M scanners, NASA has been working since 1969 to develop a new approach to remote sensing to be able to provide nominally 10 meter type resolution along with high sensitivity using multispectral linear array technology (MLA). This new technology utilizes solid-state arrays of detector elements which are laid down in lines and operated in a "pushbroom" scan mode. Other papers describe this technology, so we will not review it here.(1) As a reminder though, the pushbroom scan mode uses orbital motion to sweep the effective projection of the line array on the ground along track, while the detectors (which are oriented across track) are electronically sampled one-at-a-time at a rate to provide contiguous along track resolution elements. The experimental sensor we describe in the following paragraphs uses this technique. Programmatic exigencies have prevented exploitation of this technology until the fiscal year 1981 budget cycle, although a sensor could have been developed starting back in 1974.

It has become apparent since the launch of Landsat 1, that an increase in temporal coverage, over the 18-day cycle of the Landsat series, is necessary for a number of applications. There are three basic ways to provide this capability: (1) use nine satellites in the current 18-day Landsat orbit, (2) use satellites in geosynchronous orbit, or (3) utilize a sensor whose field-of-view can be directed to targets off the nadir in the across track direction. Financially, it is better to go with (3) if you can understand the radiometric and geometric corruptions associated with looking at large angles off the nadir. The Multispectral Resource Sampler (MRS) will be the first attempt to answer the science questions for a sensor of this type on a satellite platform. Other drivers for this new sensor include: (1) provide higher spatial resolution than the TM, (2) provide narrow ($\sim$ 20 nm wide) spectral bands and selectable bands to allow the MRS to be a facility for multi-disciplinary research, and (3) provide 0.5% sensitivity in the 20 nm bands. A programmatic driver is to put all these characteristics into a package the size and data rate of the MSS.

The MRS Design Concept

The MRS is built around the maturity of silicon integrated circuit technology. Silicon has a useful spectral response out to 1.0 μm. The technologies for the infrared spectral regions are significantly less mature, especially in terms of schedule and dollar impact to a sensor program starting in the current time line for launch in calendar 1984. Thus, the MRS is a visible/near IR sensor only.

Table 1. MRS Sensor Characteristics

Spectral Range:	0.36 μm to 1.0 μm
Spectral Bands:	4 arrays, each with 2000 detectors 5 selectable filters/array Bandwidths $\geq$ 20 nm Polarization filters

Spatial Resolution:	15 meters max
Swath Width/Modes:	15 km at 15 m (4 bands) 30 km at 15 m (2 bands) at 15 m (4 bands, 50% sampling) at 30 m (4 bands)
Radiometric Sensitivity:	Approximately 0.5% NE$\Delta\rho$ (8 bit)
Data Rate:	15 mega bits/sec.
Pointability:	2 axes + 40^o across track + 55^o along track
Speed of Pointing:	30^o/sec across track 5^o/sec along track

Table 1 shows the instrument characteristics which meet the experiment needs. First, the instrument has a gimballed mirror (see Figure 1) to direct the field-of-view to positions off the nadir in the across track direction. An additional capability is provided by gimballing the entire telescope assembly to allow along track pointing for atmospheric path length studies and stereoscopic imaging. This basically 15 meter resolution, 15 km FOV, instrument also allows alternate image sampling modes across a 30 km swath width (FOV). The data rate limit constrains each of these modes. The first is obvious; two bands at 15 meter resolution and 30 km swath width allow a wider swath for experiments where 4 band multispectral data is not critical. In the second 30 km mode, every other detector is sampled out across the 30 km swath, and sampled in such a way as to provide a "checker board" pattern on the ground. Certain statistical experiments such as determining forest species by sampling techniques can use this capability. In the third mode, two contiguous 15 meter (along track) picture elements. This will allow comparison of MRS data to the 30 meter TM data.

Figure 1. The MRS Shown Attached to a Landsat Spacecraft

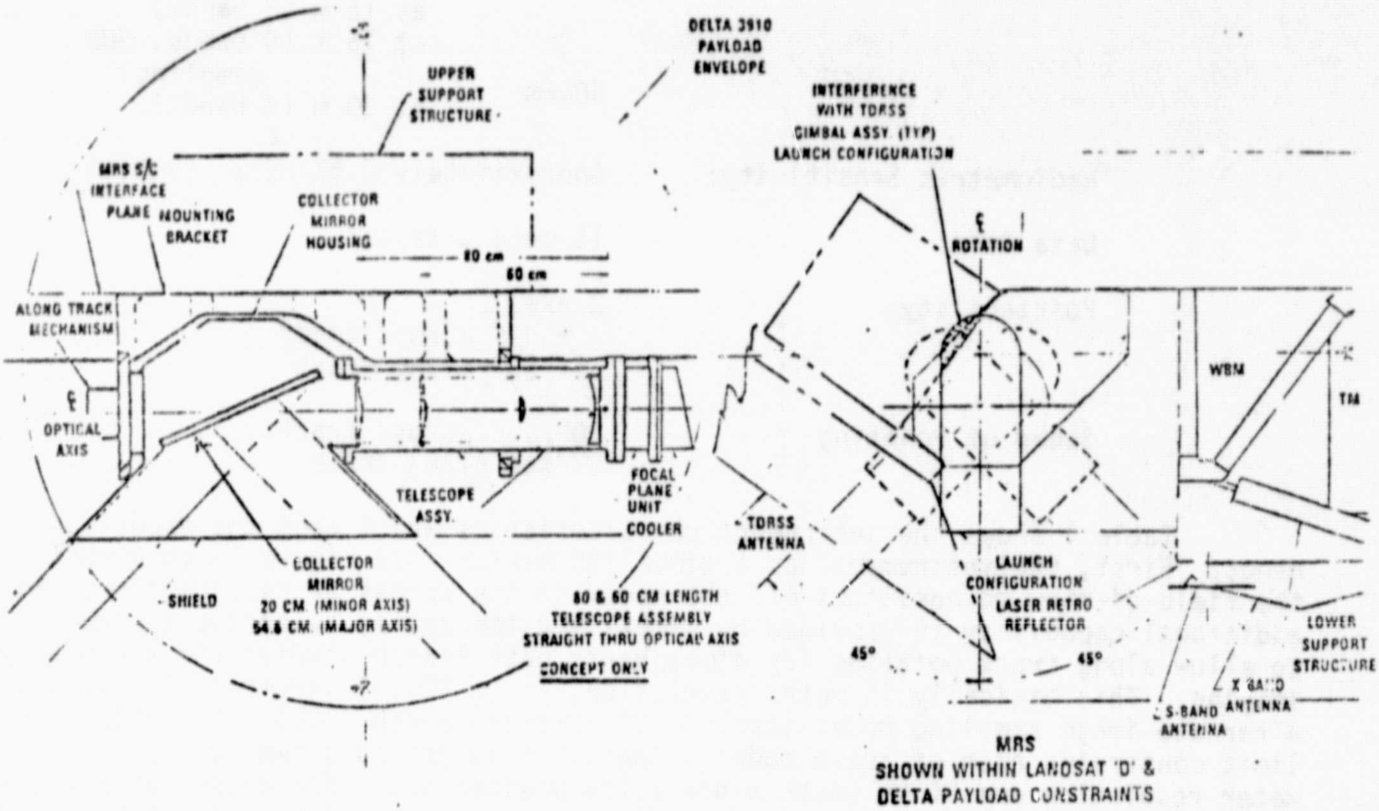

Figure 1 provides a line drawing of a basic concept for the MRS as it would appear on the Landsat spacecraft instrument shelf. The envelop constraint for this spacecraft makes it difficult to provide a 70 cm focal length to fit longitudinally along with the pointing mirror. This concept is preferred for its simplicity, and due to the fact that it places the detector arrays closest to the passive radiator plate which is used to cool the focal plane to nominally 5°C. Table 2 compares the MRS physical characteristics to those of the TM. This provides a perspective on the power of solid-state MLA technology for remote sensing. MRS is providing 15 meter resolution in a significantly smaller sensor than the TM with its 30 meter resolution.

Table 2. Comparison of MRS and TM Characteristics

	Multispectral Resource Sampler	Thematic Mapper
Optics Aperture	20 cm	42 cm
Focal Length	70 cm	320 cm
Wt	55 Kg	220 Kg
Size	1.6M x 0.5M x 0.6M	2.0M x 1.1M x 0.6M
# Detectors/Band	2000	16
Power	55 W	250 W

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Table 3 continues the comparison of the MRS to the TM. TM provides the IR spectral region, and maps a 185 km swath about the nadir. The MRS is a sampling, site specific research tool. In addition, within the spectral region available, the MRS is extremely flexible with its ability to change bandpass filters over each of the arrays. As presently planned, each array will have five in-flight selectable filters.

Table 3. Comparison of MRS and TM Characteristics

	Multispectral Resource Sampler	Thematic Mapper
Number of Spectral Bands	4 at one time, selectable from 30 by command	7 fixed
Spectral Range	0.36-1.0 μm	0.45-12.5 μm
Spectral Bandwidth	$\geq$ 20 nm	$\geq$ 60 nm
Polarization Filters	yes	no
FOV (Swath width)	15/30 km	185 km
IFOV (Resolution)	15 m	30 m
Pointing	2 axes $\pm 40^\circ$ across $\pm 55^\circ$ along	fixed nadir
Repeat Cycle (from a Landsat orbit)	2-2-1-2-2-2-1-2 (at 32° Lat)	16 days
Radiometric Sens.	0.5% in narrow bands	0.5% in wide bands
Quantization Levels	256 (8 bit)	256 (8 bit)
Data Rate	15 Mb/s	85 Mb/s

Performance Predictions

Improved Temporal Resolution

One of major features of the MRS is its ability to point across track to targets off the nadir. Figure 2 illustrates how 1 to 3 day repeat coverage is achieved from a Landsat 705 km altitude orbit. The figure illustrates the situation for a latitude corresponding to the southern U.S. On day zero, the MRS is directly overhead, and on day two, the MRS can look back to the same target by pointing off nadir 21.9°. On day four the angle is 39°, etc. The insert on the figure shows the repeat cycle for various latitudes. The 46° latitude corresponds to the North Dakota/South Dakota region; eleven views of the same site will be obtained every 16th day cycle above this latitude.

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Figure 2. Illustration of the Improved Temporal Resolution Provided by the MRS

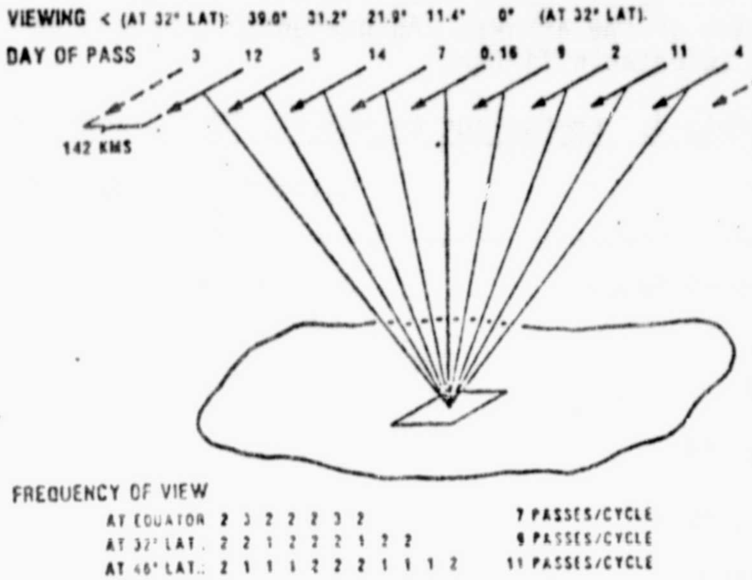

Table 4 provides the current list of filters planned for the MRS. This list was developed in conjunction with a non-NASA science advisory group for the MRS. As stated earlier, each filter wheel will contain five filters, and each wheel is indexed independently. Thus, an experimenter can choose (in-flight) from each column. Present plans call for the use of filters that pass orthogonally polarized light (these are included in the selections provided in Table 4).

Table 4. MRS Spectral Bands

		Array No.				Remarks
		1	2	3	4	
Filter Position	1	450-520 TM 1	520-600 TM 2	630-690 TM 3	760-900 TM 4	Thematic Mapper bands
	2	540-560	670-690	710-730	780-800	Vegetation
	3	840-860	880-900	730-750	400-420	Geol. Veg.
	4	360-400	TM 3 Vert.	930-950	490-510	Atmos. Land Use Polar.
	5	TM 4 Vert.	TM 4 Horz.	TM 2 Horz.	TM 3 Horz.	Polarize

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Figure 3 illustrates the baseline design for the four indexing filter mechanisms at the focal plane of the optics. Note that the element shown at the end of the barrel is the spider for the secondary of the Baker-Schmidt lens design. The corrector plates are supported at a position well beyond the secondary mirror, and are not shown on this figure.

Predicted Instrument Sensitivity

Figures 4 and 5 provide an indication of the MRS radiometric performance in terms of noise equivalent reflectivity. The NErho is defined as that change in reflectivity equivalent to the RMS sensor noise. The scene radiance is the total radiance at the satellite including a path radiance contribution for a model atmosphere with a 23 km to 27 km visibility (a so called clean rural atmosphere). At poorer lighting conditions (i.e., larger solar zenith angle), the path radiance increases in proportion to the target radiance, thus for a fixed sensor noise level the NErho increases showing degraded sensitivity. In all cases, the TM has poorer performance than the MRS in these bands. This allows the MRS to go to narrower spectral bands and still provide performance nominally equivalent to the TM in its wider spectral bands.

Figure 3. Aft Optics Design Concept for the MRS

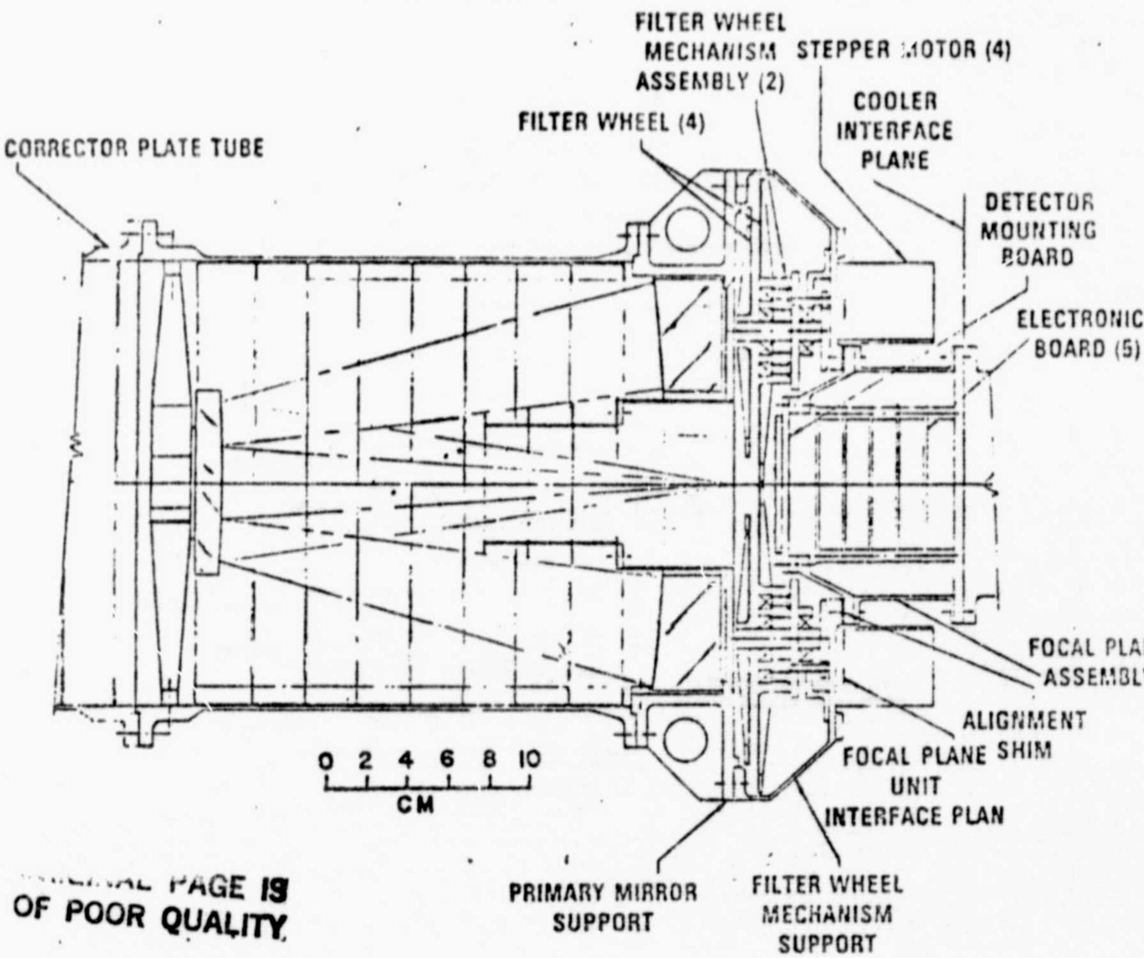

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Figure 4.

PREDICTED PERFORMANCE
MULTISPECTRAL RESOURCES SAMPLER (MRS)
SPECTRAL BAND — .45um to .52um
PERFORMANCE OVER KANSAS AT VARIOUS TIMES OF YEAR

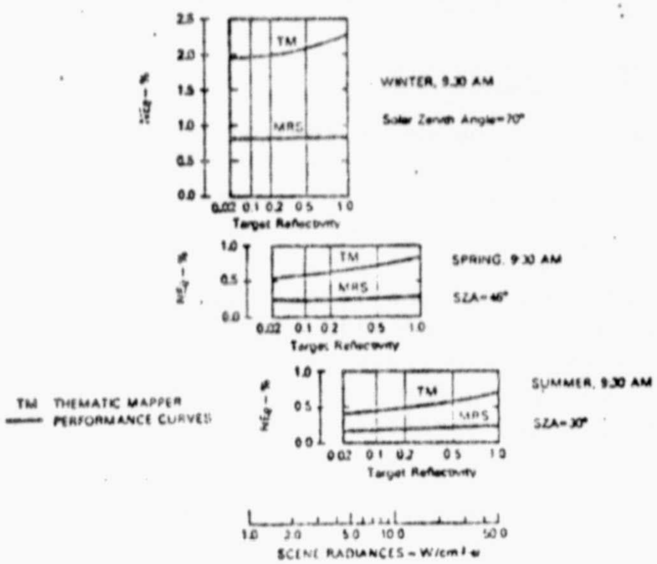
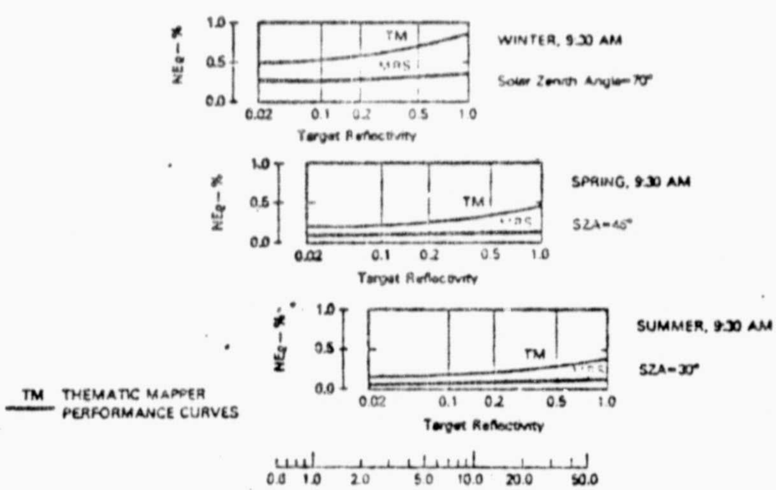


Figure 5.

PREDICTED PERFORMANCE
MULTISPECTRAL RESOURCES SAMPLER (MRS)
SPECTRAL BAND — .76um to .91um
PERFORMANCE OVER KANSAS AT VARIOUS TIMES OF THE YEAR



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The focal plane technology which provides the MRS with this performance has been state-of-the-art for several years. The performance is predicated on 15 μm by 18 μm detector apertures (the detectors are on 15 μm center-to-center spacing), 70% quantum efficiency up to 0.8 m wavelength, and nominally 500 electrons rms noise at the system level. The signal-to-noise calculation included signal level dependent shot noise root-sum-squared with the system noise level.

Final Remarks

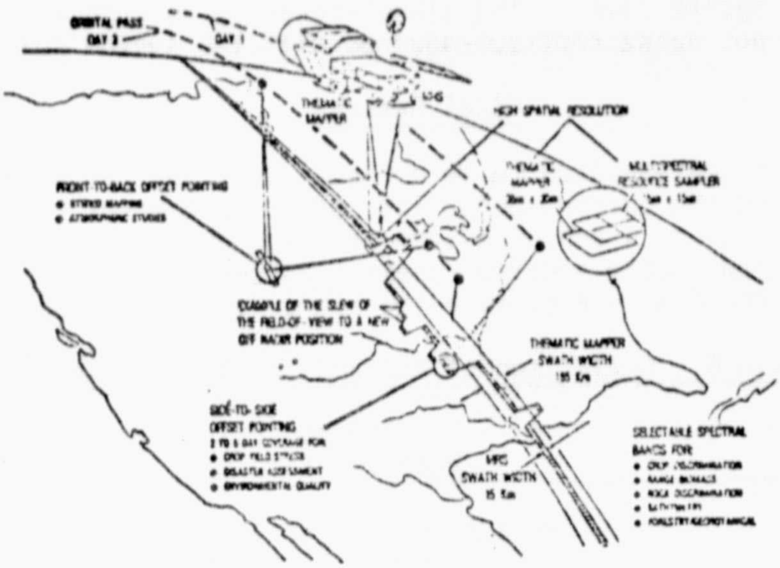
The MRS is contemplated to be a fiscal year 1981 NASA new-start instrument program. Utilizing the current capability of silicon array technologies in the visible spectral region, a sensor system has been designed in concept which has capabilities for new remote sensing research beyond that possible with the Thematic Mapper. Table 5 and Figure 6 provide the summarizing statements for this paper.

Table 5. Comparison of MRS and TM Capabilities

	Multispectral Resource Sampler	Thematic Mapper
Primary Use	Research-multidisciplinary Ag, land use, coastal processes, atmos. studies, hydrology, geology, bathymetry	Quasi-operational-Mainly agriculture and land use
Coverage	Segment Sampler	Wall-to-wall
Temporal Coverage	Every 1-2 days	Every 16 days
Spectral Coverage	Flexible-optimum for multi-discip., but only in vis/near IR	Optimized for vegetation, in vis/near IR, mid IR, and thermal
Footprint	225 sq. meters	900 sq. meters
Stereo Coverage	Yes, on sampling basis	No, except in sidelap
Atm. Correction Poss.	Yes	No
Polarization Measurement	Yes	No

<u>Figure 6.</u>

MULTISPECTRAL RESOURCE SAMPLER (MRS)



This sensor system could be launched in December 1984, on a shuttle retrieved, refurbished Landsat D.

The Multispectral Resource Sampler is the prelude to many new capabilities in remote sensing, especially at relatively high spatial resolutions. The infrared arrays will be available within the next 4 to 6 years, so that by the late 1980's a full range of pushbroom scan technology can be provided to meet the most stringent of user needs.

<u>References</u>

1. L. L. Thompson, "Remote Sensing Using Solid-Sate Array Technology," Photogrammetric Engineering and Remote Sensing, Vol. 45, January 1979, pp. 47-55.

APPENDIX B
REMOTE SENSING USING SOLID-STATE ARRAY TECHNOLOGY

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Remote Sensing Using Solid-State Array Technology*

Linear arrays provide precision geometric positioning of the detectors, very high sensitivity and favorable signal-to-noise ratio, low power consumption, and no moving optics.

ABSTRACT: *Current multispectral remote sensing of the Earth's surface from satellite platforms requires sensor systems which use mechanically moving mirrors, as in the Landsat Multispectral Scanner (MSS) and the upcoming Thematic Mapper (TM). The TM with its 30 metre ground sample distance is a complex sensor system which requires manufacturing tolerances of tenths of a micrometre and mechanical control of the scanning mirror to arc seconds. For future applications which require high resolution (10 m region) and/or narrower spectral bands in the 0.4 to 1.1 μm region without sacrificing sensitivity, a sensor system which uses solid-state linear arrays and operates in a "pushbroom" scan mode can provide the required performance. In the pushbroom scan mode, the line array of detectors is oriented perpendicular to the ground track velocity. As the along track motion scans the projection of the detectors over the scene, the detectors are electronically sampled in such a way that the entire line array is read-out in the time to advance one resolution element. The advantages of line arrays include precise geometric positioning of the detectors; very high sensitivity and favorable signal-to-noise ratio (S/N) with small lightweight optics; low power consumption; and no moving/oscillating optics. Laboratory experiments using straightforward techniques show that the precision radiometric calibration of thousands of detectors is possible. In addition, it has been demonstrated that multiple monolithic linear array devices (chips) can be assembled together to provide linear arrays with thousands of detector elements. Alignment tolerances of better than 0.3 resolution element have been achieved, and techniques have been described to improve this to 0.1 resolution element. System level noise performance has been demonstrated which allows a sensor system to be provided with 10 metre ground sample distance and with noise equivalent reflectance better than the Thematic Mapper at 30 metres.*

BACKGROUND

SINCE THE FIRST weather satellites began to image cloud patterns and to provide a synoptic view of the Earth's surface, we have been evolving ever more sophisticated sensors to help unlock the basic information in the upwelling radiance from the lands and seas. In the early 1960s, simple TV type pictures were provided. Cloud shapes and relative motions were evident, but radiometric information could not be provided by these imaging sensors. The radiometers which were built at this time required reso-

* Presented at the ACSM/ASP Annual Convention, March 1978, Washington, D.C.

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 45, No. 1, January 1979, pp. 47-55.

lutions* on the order of kilometres (Goldberg, 1968; Ostrow, 1970) in order to provide the requisite sensitivity to small changes in the target radiance.

In 1972, NASA launched the first "Earth resources" sensors into orbit (Landsat-1) and a quantum leap in resolution from approximately one to better than 0.1 kilometre was accomplished. The success of the Multispectral Scanner (MSS) and Return Beam Vidicon (RBV) sensors has been widely acclaimed. Today, 1978, these basic sensor technologies remain representative of the remote sensing capabilities from satellite platforms.

In 1977, NASA initiated new technological developments to enhance and upgrade remote sensing from satellite platforms. An evolutionary growth of the electro-mechanical scanner technology embodied in the Landsat MSS is now under development. This sensor, the Thematic Mapper (TM), is being constructed for launch in 1981. Compared to the MSS (79m IFOV,† 4 bands, 64 gray levels) the Thematic Mapper will provide improved spatial resolution (30m IFOV), additional and narrower spectral bands (seven), and increased instrument sensitivity (256 gray levels). This last improvement is equivalent to going from roughly 2 percent precision to 0.5 percent precision. As significant as the Thematic Mapper's performance improvements are, they still represent a limitation. As shown in Figure 1,* the electro-mechanical scanners have reached a plateau in development. Any further improvements in performance will be increasingly costly for only small increments in performance ability.

* Resolution as used in this article refers to the geometric footprint of the sensor due to the fieldstop of the optical system, usually the detector aperture.

† Instantaneous field-of-view.

Pushbroom Scan Technology

NASA/Goddard has had under development since the early 1970s a sensor technology that allows a second quantum leap in performance for remote sensing. This new generation of sensor operates on a principle different from the electro-mechanical scanners.

Pushbroom scanning is a term which describes the technique of using the forward motion of a satellite platform to sweep a linear array of detectors oriented perpendicular to the ground track across a scene being imaged. This technique is illustrated in Figure 2, which shows an optical system imaging the ground scene on a line array of detectors. One array is typically used for each spectral channel. Satellite motion provides one direction of scan and electronic sampling of the detectors in the crosstrack dimension provides the orthogonal scan component to form an image. The detector array is sampled at the appropriate rate so that contiguous lines are produced.

* The Merit Function of Figure 1 is explained in Appendix A.

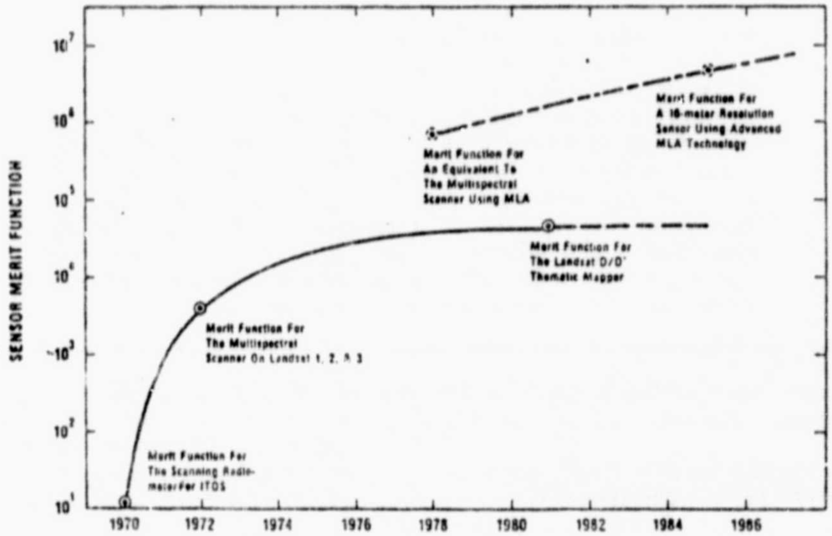

FIG. 1. Historical trend in Earth-viewing electro-mechanical scanners.

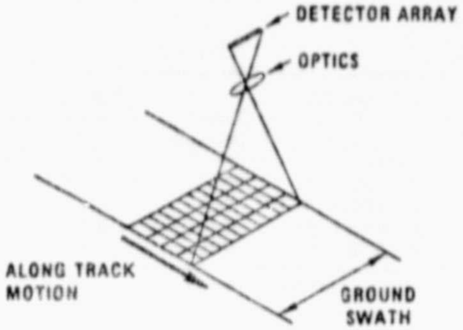

FIG. 2. Geometry of pushbroom scan technique.

There are two principal advantages to the pushbroom scan techniques using long linear arrays of solid-state detectors. First, complex mechanical scan mechanisms are eliminated. Second, this approach allows the photon flux from the scene to be integrated during the time required for the instantaneous field-of-view (IFOV) to advance the dimension of one resolution element on the ground. For a quantitative indication of what this means, consider that the dwell time per resolution element in the Landsat Multispectral Scanner (MSS) is 14 microseconds. Using the pushbroom approach and the same orbital conditions, the dwell time can be increased to approximately 12 milliseconds for the same resolution element dimensions. This allows an increase of more than a factor of 800 in the signal generated and stored at each detector position. The improvement in signal-to-noise ratio is significant, and permits smaller aperture optics to be used, with a consequent reduction in size and weight.

Another advantage of solid-state technology is that high cross-track geometric fidelity is achieved along each linear array to the extent that the position of each individual detector is precisely known. Spacecraft motions limit the ability to attain geodetic fidelity along track, but corrections for attitude during ground data processing should reduce the variations in effective ground distance between successive scans to a minimum. Besides the geometric accuracy within a single array, accurate positioning of arrays for each spectral band in the image plane with respect to each other allows very close multispectral registration of the resulting images.

It is clear that operation in a pushbroom scan mode has many desirable features. The trick is now to provide the many thousand element detector arrays required to subtend the crosstrack swath for Earth resource applications. Typically a 30-m resolution pushbroom sensor requires 6300 detectors per spectral band to subtend a Landsat type swath. Imagine the complexity and cost of providing this large an array with 6300 individual point detectors, each with a wire bond to discrete amplifier components. Each signal channel (detector) would have in excess of 30 components associated with it, giving almost 200,000 parts per band and 800,000 parts per instrument. There has to be a better way.

Solid-state integrated circuit technology provides the answer. On a single monolithic chip of silicon, hundreds to over a thousand detectors can be manufactured. In addition, low noise "on-chip" amplifiers and electronic multiplexing circuits are provided simultaneously. By manufacturing all these elements on a single integrated circuit, it is now possible to have an array of hundreds of detectors which interface to the rest of the world with only a few wire bond connections. Figure 3 shows one approach to array organization to illustrate how the detector signals are sampled and read off the chip. Each detector is sequentially connected, one at a time, to an on-chip amplifier. A circuit called a dynamic shift-register controls the sequence of the connections to the amplifier. This approach allows a relatively small area of the array to be dedicated to low noise analog signals, and a different area of the chip to be used for digital switching operations. The yield (the number of working devices out of the total lot) of solid-state devices is directly proportional to the area of a chip. Digital circuits are relatively more fault tolerant than analog elements. Minimizing the area devoted to low noise analog signals improves the yield of detector array chips and, thus,

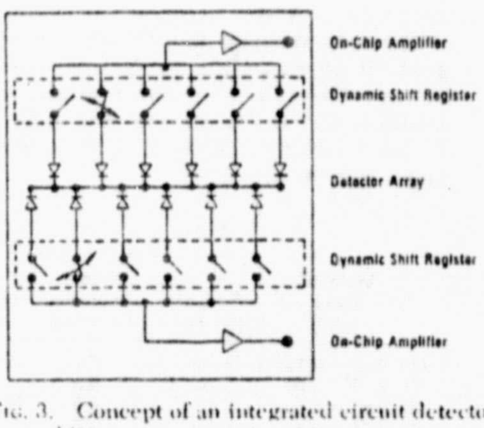

FIG. 3. Concept of an integrated circuit detector array chip.

should lower the cost per detector. There are other chip architectures which have different desirable features (NASA, 1972). The point is that solid-state integrated circuit technology provides the means to deliver large linear arrays for pushbroom scan sensor systems.

NASA/Goddard Space Flight Center, through a contract with Westinghouse Electric Company (Westinghouse, 1976), developed a detector array technology which demonstrated performance adequate for a 10-metre resolution multispectral imaging radiometer. The work started in 1972 and was completed in 1976. This work with Westinghouse provides the foundation for the decision to pursue a program to develop a space qualified multispectral remote sensing instrument using solid-state linear arrays.

Performance of Pushbroom Systems

Radiometric Sensitivity

What I would like to do now is to determine the required performance to provide 0.5 percent sensitivity in four spectral bands for a variety of scene conditions, and then show how well a pushbroom scan sensor with 10 metre "resolution" meets these requirements. The spectral bands chosen are the visible/near IR bands of the Thematic Mapper. Let me, in addition, define 0.5 percent sensitivity as the change in target reflectance ($\Delta\rho = 0.005$) equal to the RMS noise of the sensor system. This is the noise equivalent reflectance, $NE\rho$.

First, take a scene condition (Fraser, 1975) that roughly corresponds to summer in the southern United States. The solar angle to the zenith is 10°, and the atmosphere approximates a clean rural condition (visibility = 27 km) (Table 1). The time of day is 10:30 A.M.

The second scene condition is more stringent. It corresponds to spring or fall in central Canada. The solar angle to the zenith is 45°, and again the atmosphere has 27 km visibility (Table 2). I have lowered target reflectance, also.

Table 1

Spectral Band (μm)	Target Reflectance	Scene Radiance (w/m²-sr)	Required S/N*
(1) 0.45 – 0.52	0.10	7.0	52
(2) 0.75 – 0.60	0.20	9.8	65
(3) 0.63 – 0.69	0.20	6.0	57
(4) 0.75 – 0.91	0.50	24.6	117

* To provide $NE\rho = 0.005$.

Table 2

Spectral Band (μm)	Target Reflectance	Scene Radiance (w/m²)	Required S/N*
(1) 0.45 – .52	0.02	3.0	38
(2) 0.52 – .60	0.10	4.4	48
(3) 0.63 – .69	0.10	2.3	35
(4) 0.75 – .91	0.20	7.0	52

* To provide $NE\rho = 0.005$.

The following parameters describe the salient characteristics of the pushbroom scan sensor which will attempt to meet the requirements in Tables 1 and 2. Assume a nominal orbital altitude of 700 km:

Optics Aperture: 30 cm
Focal Length: 105 cm
Instantaneous field-of-view: 14.3 μrad
Optical Transmission (Filters included): 0.3
Signal Integration Time: 1.50×10^{-3} seconds

To complete the characterization of this sensor, assume now a very conservative noise level of 1000 electrons RMS.*

In the current technical literature noise levels of 100 to 200 electrons RMS are routinely reported, and have been for several years (White, 1974). Table 3 lists the noise level for each spectral band in units equivalent to exposure density at the focal plane. Remember, the detectors integrate photon flux from the scene in the pushbroom scan mode.

NOTE: Area of Detector = $14\mu m \times 18\mu m = 2.7 \times 10^{-10}\ m^2$

Quantum Efficiency = 0.7 (bands 1-3)
0.5 (band 4)

With the above parameters the signal-to-noise ratios listed in Table 4 are provided in each spectral band for the conditions of Tables 1 and 2.

Table 3

Spectral Band No.	Noise Equivalent Signal (10^{-6} J/m²)
(1)	2.19
(2)	1.81
(3)	1.59
(4)	1.77

* This level of noise was measured in 1972.

TABLE 4

Spectral Band No.	S/N Table 2 Required	S/N Pushbroom	S/N Table 1 Required	S/N Pushbroom
(1)	38	38	52	88
(2)	48	68	65	145
(3)	35	41	57	103
(4)	52	107	117	339

Table 4 shows that a pushbroom scan sensor can indeed provide the required performance at 10 metre resolution. In addition, if either 500 electrons noise or an increase in quantum efficiency to 0.95 or a combination are used (as would be appropriate for current array technology), then spectral bands as narrow as 20nm wide could be used in the sensor's design. As a matter of comparison to the Thematic Mapper, with its 30 m resolution and 42 cm optics aperture, Table 5 is provided (for Table 2 conditions).

Another way of showing sensor performance at different scene conditions is shown in Figure 4. Based on previous definitions, this figure is self-explanatory.

DETECTOR ARRAY GEOMETRIC FIDELITY

Figure 5 shows an array assembled under the Westinghouse program. Using 18 silicon chips, each with 96 detectors, an array of 1728 detectors was provided. Although current technology can now provide single chips with over 1000 elements, this illustration serves to show how arrays of 6000 or more detectors (as needed in a Thematic Mapper application) could be assembled. The detector positions on each chip are precision controlled to 0.05 of a resolution element. The chips in the 18-chip array were aligned to a precision of 0.3 of a resolution element size with a cumulative error over the length of the array of 0.5 of a resolution element. The depth of focus was controlled to ± 12 μm.

The advantage of the approach shown here is that the edges of these array chips are precision manufactured to allow contiguous (!) alignment of detector elements on a chip-to-chip basis. Ground data processing is simplified. Other suggested approaches end up with a bi-linear configuration where the chips are spatially staggered over distances equivalent to 200 resolution elements. Another advantage of a segmented contiguous array is that cordwise approximation to curved focal surfaces are permitted. In high resolution systems, this may be required. The singular disadvantage of the contiguous approach is that typically one 15 μm space is required at the chip edges. This is equivalent to having a dead element in the array. This may or may not be a significant disability depending on the application under consideration.

TABLE 5

Spectral Band No.	S/N Pushbroom	S/N Thematic Mapper
(1)	38	35
(2)	68	72
(3)	41	45
(4)	107	122

RADIOMETRIC CORRECTION

Perhaps the single most frequent concern regarding pushbroom technology is the question, "How are you going to destripe the data from *thousands* of detectors, when you have problems with the 24 detectors on the Landsat Multispectral Scanner (MSS)?" I would like to let a picture speak for itself.

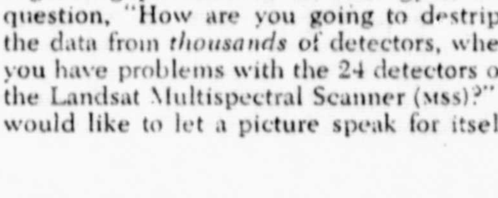

FIG. 4. Noise equivalent reflectance versus solar zenith angle for a system with a 10 m IFOV using current detector technology and 21 cm optics.

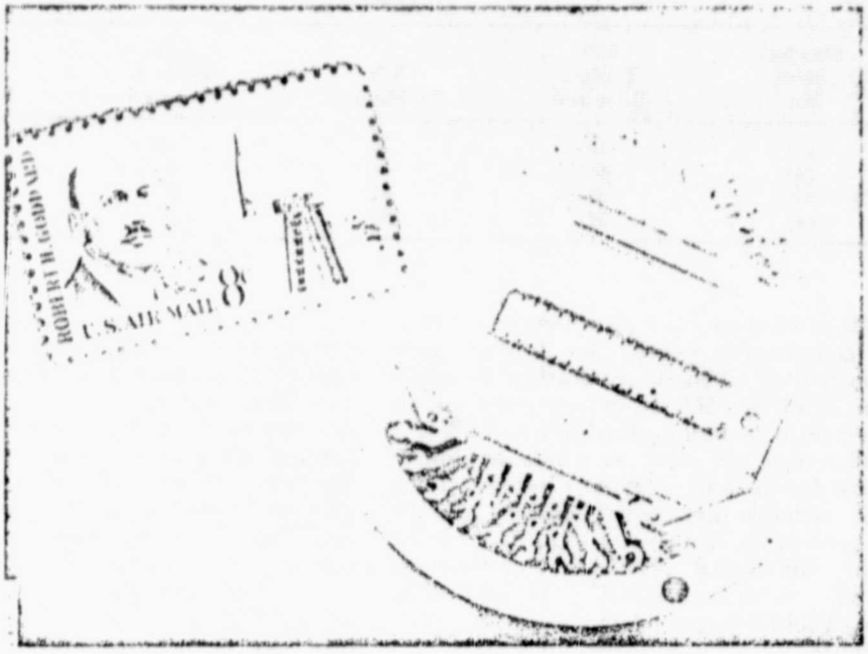

FIG. 5. A 1728-element detector array manufactured from 18 individual integrated circuit chips. The detector array is the dark line at the center of each chip.

Figure 6 shows a positive print of a radiometrically corrected image made using the 18-chip array on a laboratory scene simulator. A USGS high resolution black-and-white transparency was back illuminated, spectrally filtered, and then imaged into the array. The image format is 1728 by 1728 lines per picture width. The full scale spectral radiance level corresponds to Band 4 in Table 1. The integration time was 1.44 millisecond (roughly that for 10 metre resolution on a satellite). The furrows in the field in the pictures center are approximately two resolution elements center-to-center.

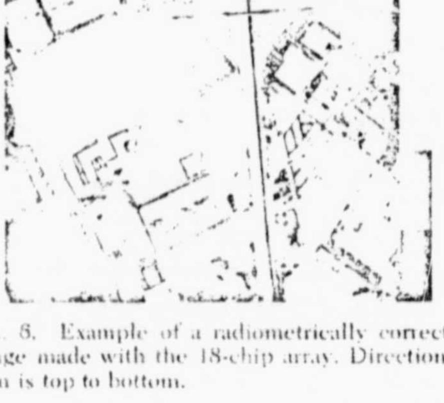

FIG. 6. Example of a radiometrically corrected image made with the 18-chip array. Direction of scan is top to bottom.

Careful examination is required to determine the direction of scan. The tip-off is some line structure where a dead element was cosmetically corrected by averaging between adjacent working elements. Regardless, a good job of radiometric corrections has been achieved. To show that this one image is not a fluke, Figure 7 shows a montage of four separate pictures whose individual image format is 576 by 576 lines per picture width. Again, radiometric correction has removed the detector-to-detector variations.

The critical elements in radiometric correction of detector arrays are

- Provide a highly stable operating temperature at the array, and stable bias voltage;
- Provide updates of calibration files at the beginning of an orbital pass and at the end to determine if any drifts have occurred;
- Have an extensive ground calibration procedure to catalog array performance under various bias voltage and focal plane temperature configurations; and
- Plan to have most elements corrected using a simple equation of a straight line. For the other elements, either linear segment approximations with five or more calibration points per detector or some

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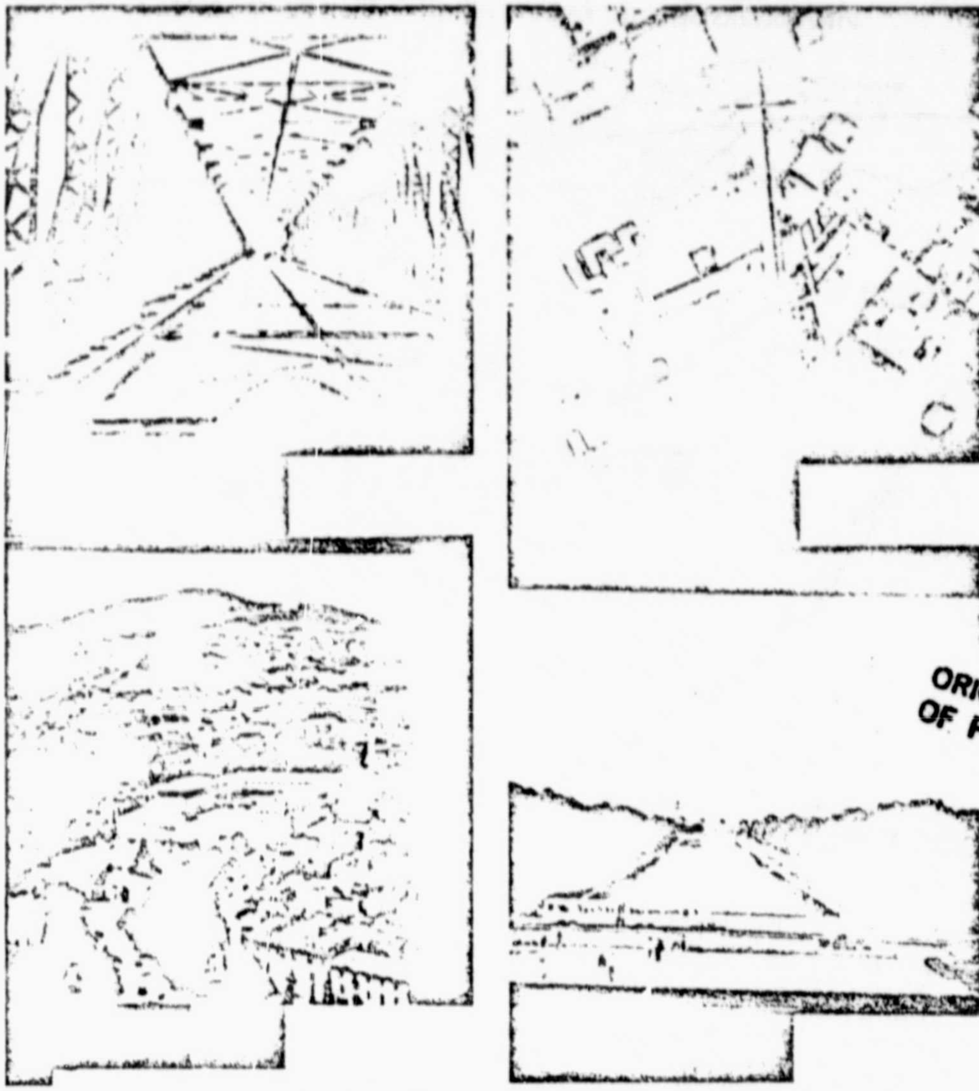

FIG. 7. Examples of radiometrically corrected imagery from a 576-element detector array.

complex polynomial fit will be required. Good software is required to do the job efficiently.

CONCLUSION

For the visible/near IR spectral region, silicon pushbroom scan arrays have matured and are ready for application to remote sensing from satellites. Significant performance is available, and can be used to provide a wide range of configurations optimized for specific applications. Figure 8 shows one sensor concept. This sensor can be used for agricultural multitemporal sampling. This sensor provides two to five day return coverage to any place on the Earth's surface and stereographic imaging for topographic mapping.

Extension of the spectral response of arrays into the 1 to 5μm and 8 to 14μm region will be developed over the next four years under NASA contracts. The military has provided the technology base, and we will attempt to optimize that base for our applications. A positive view of the future indicates we will be ready in 1984, and a first launch of a pushbroom scan sensor with all the spectral bands of the Thematic Mapper is anticipated by 1988.

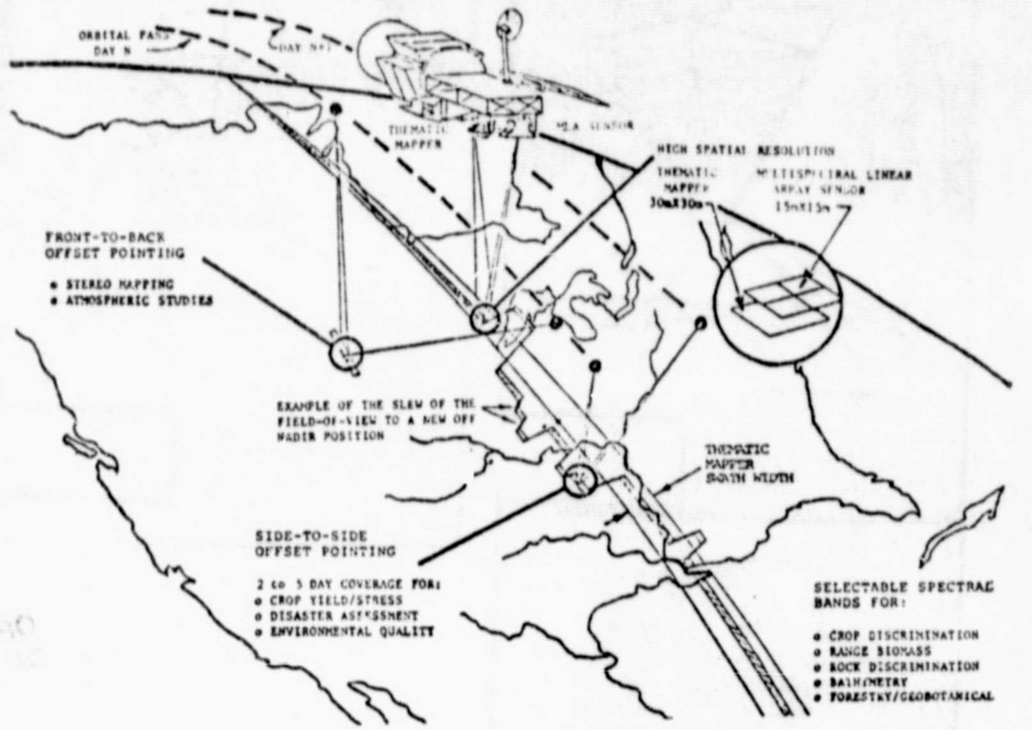

FIG. 8. Concept of a multispectral linear array sensor (MLA) which provides agricultural repeat coverage and stereo.

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Appendix A

Merit Function for Historical Trends in Sensor Development

First, any merit function used should increase in numerical value with improvements in performance. Secondly, the inputs to the merit function should be based on factors that are generally accepted as indications of improved performance. To this end, the factors considered include

- Resolution (in terms of angular subtense),
- Number of spectral bands,
- Spectral bandwidth,
- Signal-to-noise ratio for a specific spectral radiance that is used as a common input to each of the selected systems.

In order to develop the desired merit function for sensor systems, we start with the equation for calculation of signal-to-noise (S/N);

$$S/N = \frac{\pi(D_o^2)\,(\text{IFOV})^2\,(\tau_o)\,(N_\lambda)\,(\Delta\lambda)}{4\,(\text{NEP})}$$

where, D_o is the optics diameter, IFOV is the instantaneous field-of-view, τ_o is the effective optics throughput, N_λ is the spectral radiance, and $\Delta\lambda$ is the spectral bandwidth. The numerator calculates the radiant power at the detector, and the denominator expresses the system noise as the radiant power at which the S/N equals one (Noise Equivalent Power, NEP).

The next step is to rewrite the equation above as a proportionality statement:

$$\frac{1}{\text{NEP}} = \frac{\text{S/N}}{(D_o^2)\,(\text{IFOV})^2\,(\Delta\lambda)}$$

System sensitivity measured in NEP is an important indication of performance, and the inverse gives a numerically increasing factor for improvements in performance (i.e., NEP becomes smaller).

This is the basic merit function. However, I want to expand this relation to include factors that indicate the increasing sophistication of sensor systems. The first additional factor is to make the relation directly proportional to the number of spectral bands. Next, consider scan efficiency. As the years have gone by, we have worked very hard to increase scan efficiency. The merit function is made directly proportional to this factor. Lastly, it can be shown that the mechanical scanners' optical systems do not operate anywhere near the diffraction limit in the visible spectrum, in terms of IFOV size compared to the diffraction blur size for the optics diameter provided. This has been the case because increased optics diameter was required to provide the specified S/N. To consider the penalty of increased sensor size to provide the required sensitivity, I now modify the (D_o^2) term to become the sensor density (total weight divided by telescope volume).

The Merit Function for visible spectral band performance can now be written

$$(\text{Merit Function})_{\text{vis}} = \frac{\text{S/N}\;(N)\,(WT)\,(\eta) \times 10^{-11}}{(D_o^2)\,(FL)\,(\text{IFOV})^2\,(\Delta\lambda)}$$

where the new terms in the expression are (N), the number of spectral bands; (WT), the sensor weight; (η), the scan efficiency, and (FL), the optics focal length. The multiplying constant is used as a matter of convenience to scale the ordinate.

APPENDIX C
CORRESPONDENCE

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Canada

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613-995-9671

June 20, 1979.

Dr. Edward Kanemasu,
Kansas State University,
765 College Heights Circle,
Manhattan, Kansas 66502,
U.S.A.

Dear Ed,

In principle, I agree with the draft copy of our Agricultural Panel Suggestions. I would like to add to Question 1, if possible, that NASA engineers look into changing the filter wheel concept to more modern concepts of scanning the spectral band from 380 - 800 nm such as an optical multichannel analyzer (OMA) or a circular variable filter (CVA). In the OMA technique there would be no moveable parts, and the spectral resolution would be far superior than any interference filters used in the filter wheels. Each individual researcher would be able to select the spectral ranges of his interest. This technique is available and is used by industries such as Tektronix and others. The spectral information would be taken simultaneously from 380 - 800 nm at say 10 nm intervals. Each photodiode in the linear arrays would be assigned a specific 10 nm wavelength band. The information from the linear array can be stored on memories, and if someone needs five spectral bands, then it selects from the memory whichever band is suitable to him. Using the CVA technique, only one wheel would be used, but the spectrum from 380 to 760 nm can be covered with a spectral resolution of 5 nm or better.

With all other suggestions I am totally agreeable.

Yours Sincerely,

Eugene J. Brach, Head
Engineering Research Service
Section.

EJB/kb

P.S. Question 3.

3.3.3. Should be changed to read: "Experiments should include agrometeorological expertise and observation".

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James C. Hammack
DMAHTC Code STT
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20315

Charles Schnetzler
NASA GSFC Code 932
Greenbelt, Md.
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Dear Charles:

The Multispectral Resource Sampler (MRS) as described in your paper very closely follows the requirements for a Photobathymetric Multispectral Scanner (PMS) that I provided to you last year. As you will recall, the PMS was originally submitted via the Department of Defense, (DDR&E for Strategic and Space Systems) as the Defense Mapping Agency's requirement for an unclassified bathymetric sensor on the Seasat-B. It was the result of several years of photobathymetric research by NASA, NOAA, and DMA. It was put into the submitted format as the result of consutlations with Fabian Polcyn, Dr. Colvocoresses, and Dr. Barker to address penetration of clear water to reveal shallow seas features of signifance to navigational safety as well as to provide the best capability to provide data from which actual water depths could be computed. The MRS appears to provide much of these needs. (DDR&E paper enclosed).

In the last couple of years, we have been exploring several additional ways to detect submerged hazards. These methods will not yield depths as accurately as the photobathymetric approach but they work in turbid water and can reveal major features several times deeper than optical methods. They primarily use analysis of ocean surface characteristics caused by the interaction of ocean dynamic processes with the submerged features. (See attached Technology Assessment and notes entitled Multisensor Exploitation to Improve Nautical Charts). The pointability of the MRS can be exploited to image the sun glint area in order to reveal such surface pattersn. This capability can also be enhanced by the choice of orbits. A non-sun synchronous orbit would provide both optimum lighting conditions for penetration and for sun glint acquisition. I do not have any particular recommendations for orbit, this will be a point of discussion once a vehicle is found for MRS. We hope to have used Landsat and other sensors to have pinpointed specific areas where MRS or PMS can be used for maximum benefit. (As you are probably aware, NASA has turned Landsat on over ocean shallow seas areas for DMA. We are currently phasing up a program to search and evaluate this imagery.)

With regard to the selectable spectral bands, it sounds as if we should be able to "dial" the best set of spectral bands for the water mass to be imaged. With clear ocean waters, the blue and green bands can be selected to provide the best penetration. With coastal waters, selections can be made closer to the yellow. I need to have Fabian Polcyn or Dr. Barker look at the respective placement

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of optimum bands on the filter wheel so that the best selections are not mutually exclusive. We hope to be able to use band ratioing with three bands to extract bottom reflection so that we can compute ture depths. The fourth band selected will be either red or near infrared to provide shoreline and control imagery. There is also some question as to the Landsat band six and its capability to penetrate water. We are consistently seeing shallow features on six that do not appear on seven. We have not been able to define whether there are actually some features above water at these places. Fabian has even suggested that there might be some cross over or leakage from the other channels. Our research cruise this summer will try and resolve some of this doubt.

It might be beneficial to have a seperate wheel for selection of the polarization options. The best results for our interests would be polarized blue or green bands. We are finding the sun glint on Landsat offers a significant contribution to the signal with respect to the depth extraction algorithms.

Additional considerations must be made with respect to the pointing and positioning of the satellite and the acquired image if we are to make effective use of the system to support charting. I refer you to the original DMA requirements.

Finally, I would like to remind you of our original discussions concerning the radiometric sensitivity requirements for a photobathymetric sensor. Since the light returning from the ocean bottom has twice traversed the water column, each time undergoing exponential attenuation, a PMS will have more benefit if each radiance quantization level could represent sonthing approximating uniform depth increments. At best, it should have more of its quantization levels spread over the range of photometric response that represents the signal range from the ocean's bottom. Perhaps a compromise for land and water viewing could be reached by a carefully thought out compression of the output counts as a function of source radiance. Proper compression of the Landsat data by a logarithmic signal compression not only improves photomultiplier signal to noise, it also provides better bathymetric potential than does the linear compression. Note also, that the present Landsat quantization, even in high gain, leaves much to be desired since the lower radiance values of a shoal area are representing a much larger range of depths than does a near surface radiance value. Perhaps another alternative for consideration would be different compression options, selectable by ground control at the user's option.

All in all the MRS seems to offer much more capability to provide useful bathymetric data than the Landsat or Thematic Mapper Scanners. I look forward to hearing the results of your workshop. I will be away on the research cruise until 25 June and may depart for the second cruise around the eighteenth of July. I should be back in the Washington area anytime following 3 August.

Yours,

James Hammack

James Hammack